FCC

FCC Feasibility Study with a focus on Flavour Physics opportunities
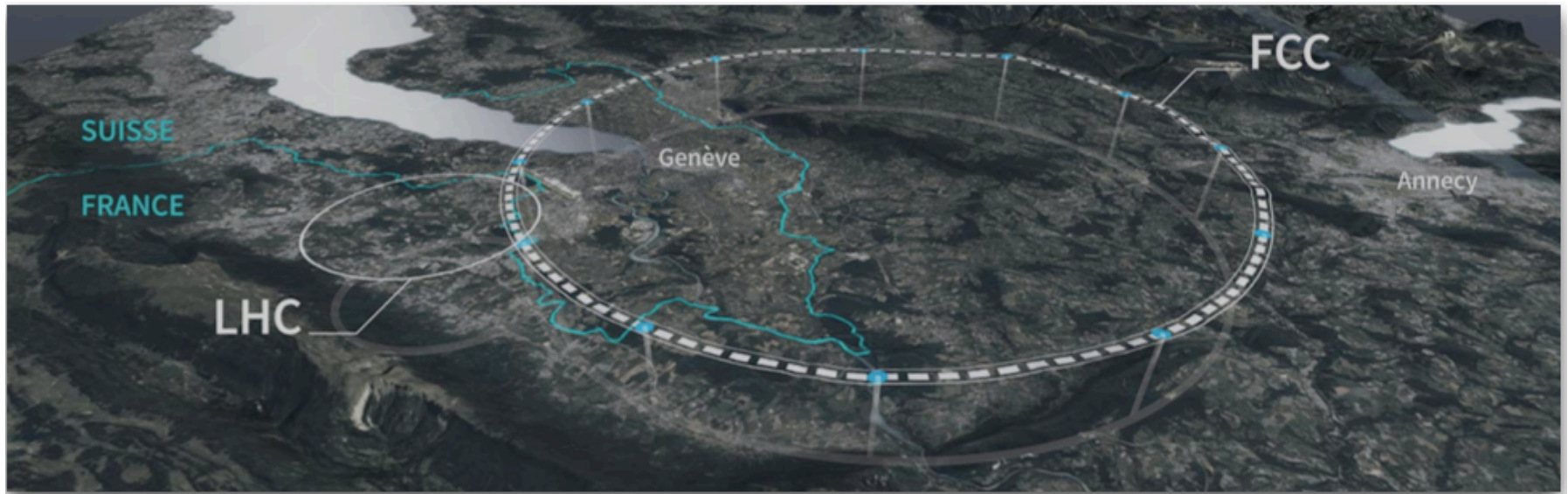
Stéphane Monteil,
Clermont University, LPC-IN2P3-CNRS.

Outline

1. FCC-ee physics programme

2. Feasibility Study key points

3. The Physics case at large (and detectors)

4. Flavours@FCC-ee: setting the scene

5. Review of current activities

6. Focus on two analyses

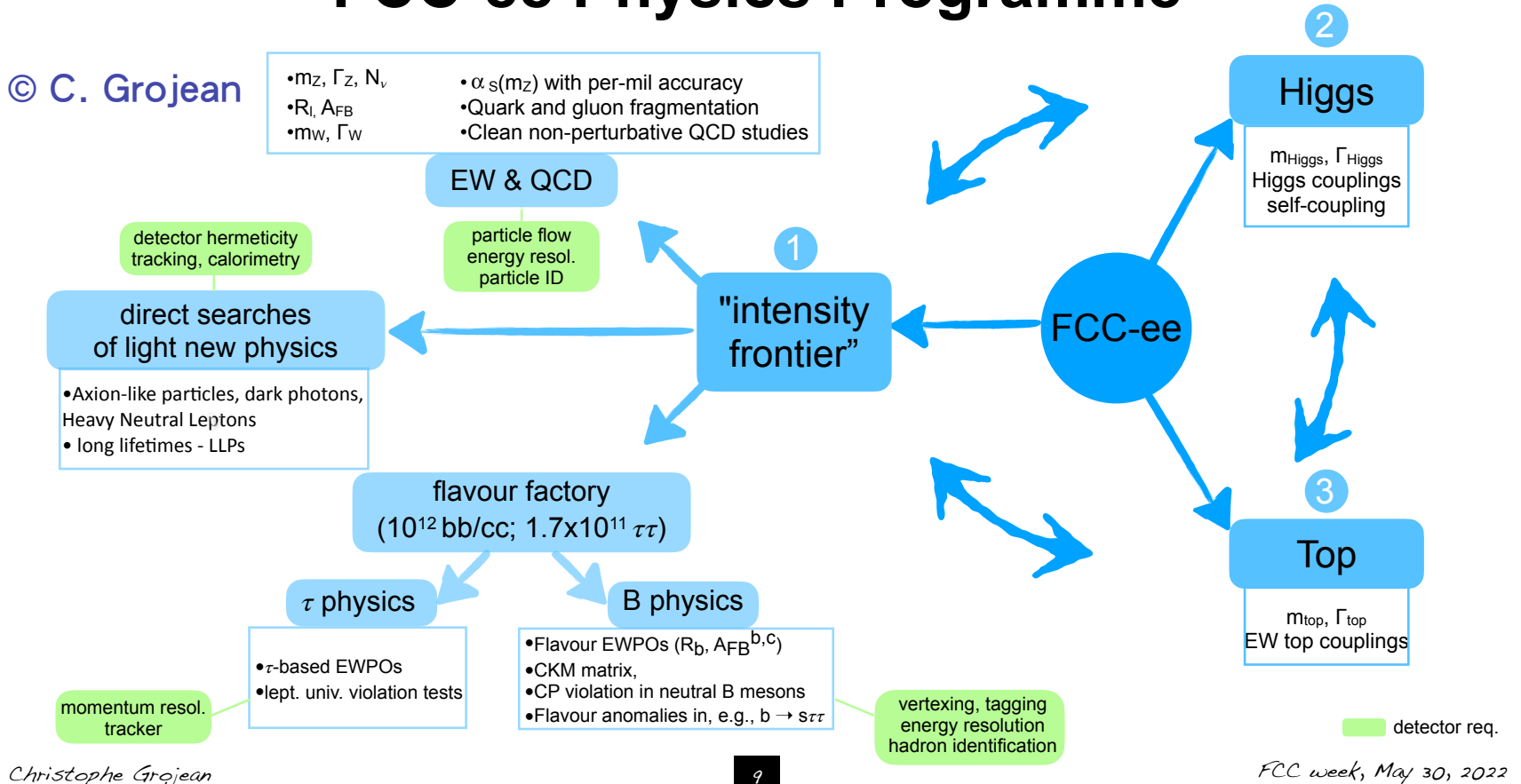7. Connecting some dots: Flavours, EWPO@Z and top

8. Summary

1. FCC-ee Feasibility Study. Motivation.

- Next-generation particle collider housed in a 90km underground tunnel

- Building-up on the CERN accelerator complex …

- … and building-up on the successful LEP / LHC strategy: implementation in stages with first an e+e- machine, followed by a high-energy hadron collider.
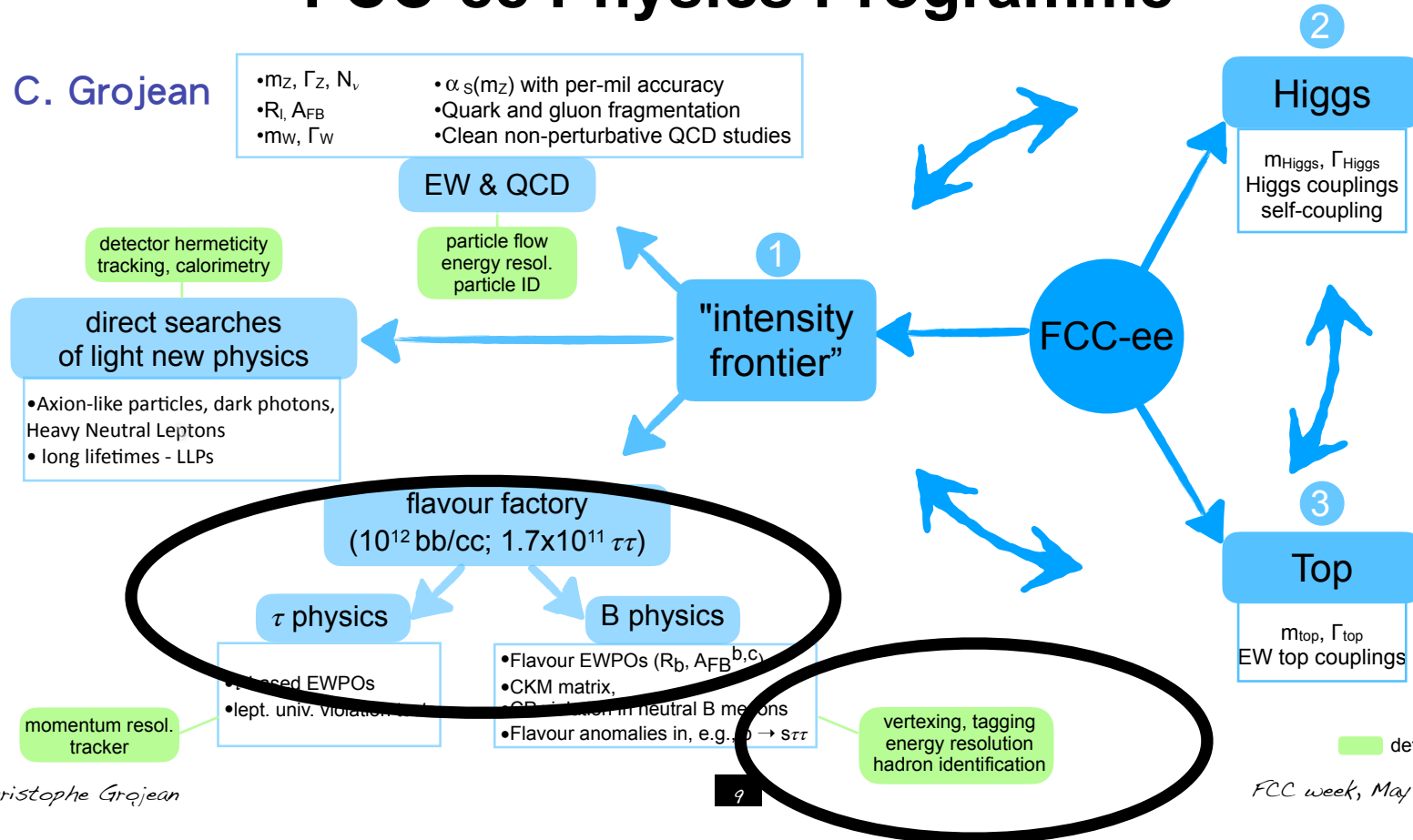
FCC-ee Physics Programme

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•m_Z, Γ_Z, N_ν	• $\alpha_S(m_Z)$ with per-mil accuracy
•R_l, A_{FB}	•Quark and gluon fragmentation
•m_W, Γ_W	•Clean non-perturbative QCD studies

EW & QCD

particle flow
energy resol.
particle ID

detector hermeticity
tracking, calorimetry

**direct searches
of light new physics**

•Axion-like particles, dark photons, Heavy Neutral Leptons
• long lifetimes - LLPs

"intensity frontier" 1

FCC-ee

Higgs 2

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

Top 3

m_{top}, Γ_{top}
EW top couplings

flavour factory
(10^{12} bb/cc; 1.7×10^{11} $\tau\tau$)

τ physics

•τ-based EWPOs
•lept. univ. violation tests

momentum resol.
tracker

B physics

•Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
•CKM matrix,
•CP violation in neutral B mesons
•Flavour anomalies in, e.g., b → s$\tau\tau$

vertexing, tagging
energy resolution
hadron identification

detector req.

Christophe Grojean

9

FCC week, May 30, 2022

• Triptych: Higgs / Top / EW factory (Intensity).

FCC-ee Physics Programme

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- • R_l, A_{FB}
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"intensity frontier"

FCC-ee

Higgs

m_{Higgs}, Γ_{Higgs} Higgs couplings self-coupling

Top

m_{top}, Γ_{top} EW top couplings

flavour factory (10^{12} bb/cc; 1.7×10^{11} $\tau\tau$)

τ physics
- τ-based EWPOs
- lept. univ. violation...

B physics
- • Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
- • CKM matrix,
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momentum resol. tracker

vertexing, tagging energy resolution hadron identification

detector req.

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- • Probable imo that Flavour Physics requirements are the most demanding in vertexing, PID, calorimetry
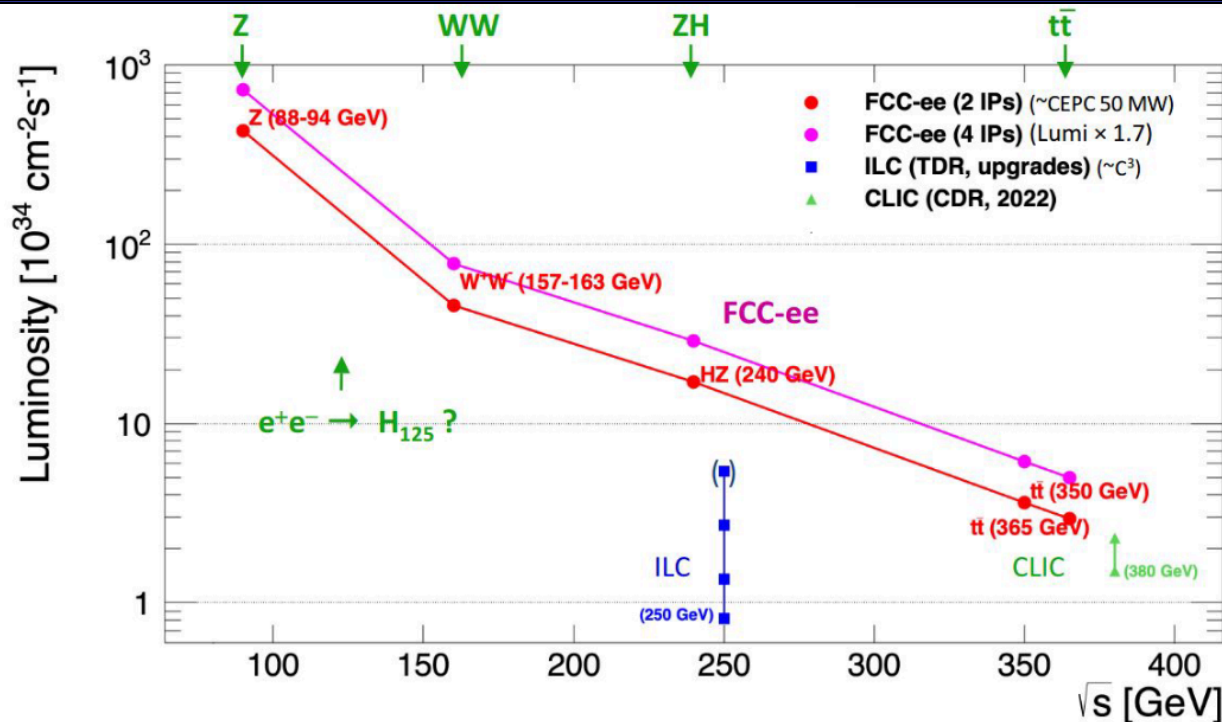
- We're speaking of 10^5 *Z*/s , 10^4 *W*/h, $1.5 \cdot 10^3$ *H* and top /d, in a very clean environment: no pile-up, controlled beam backgrounds, *E* and *p* constraints, ~w/o trigger loss.

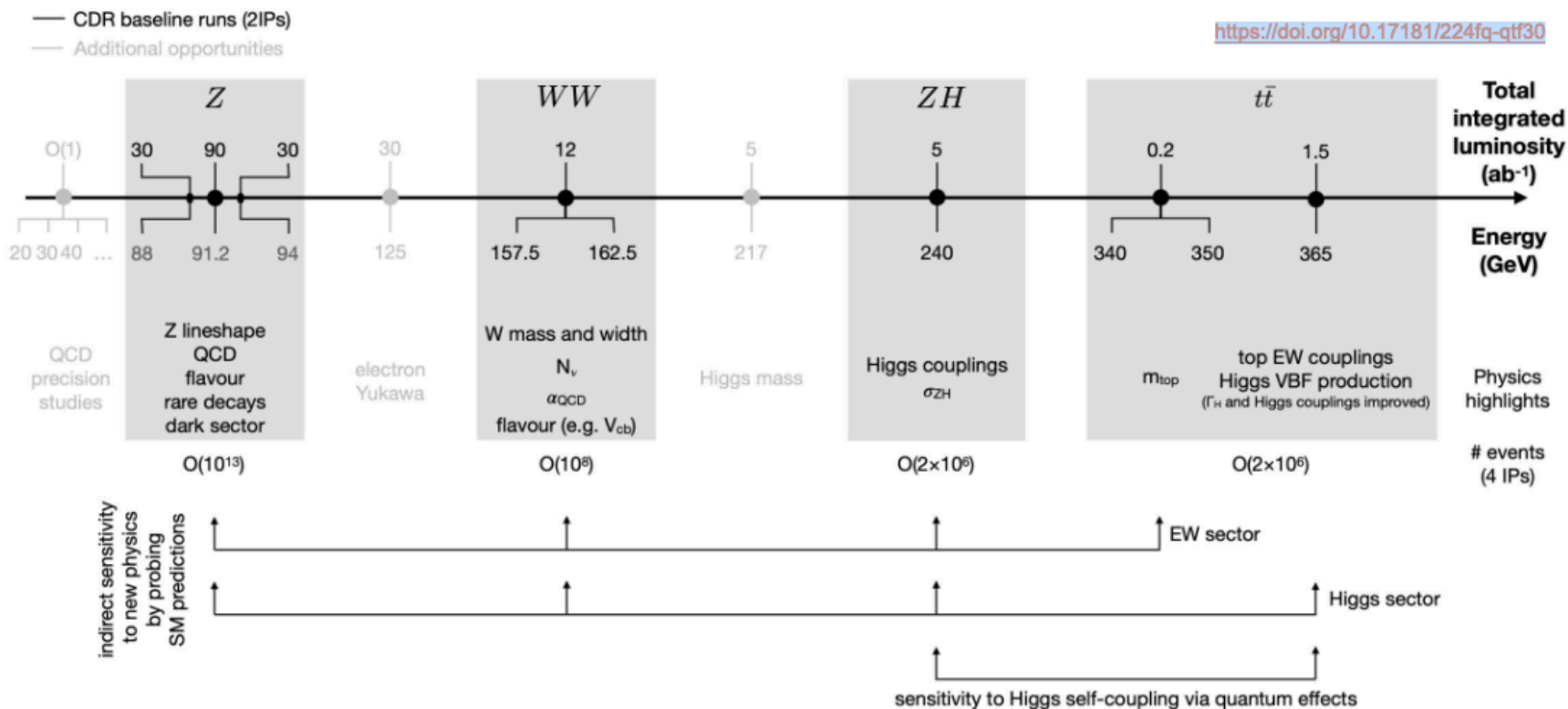- In particular, you do the LEP in a minute! Some Flavour measurements are still dominated by LEP experiments.

FCC

- Baseline:
    - 16 years nominal program.
    - 4 interaction points.
    - Versatility in run scenarii (*e.g.* could start w/ Higgs run)
    - Possibility of additional runs (*e.g. e⁻* Yukawa w/ 125 GeV run).
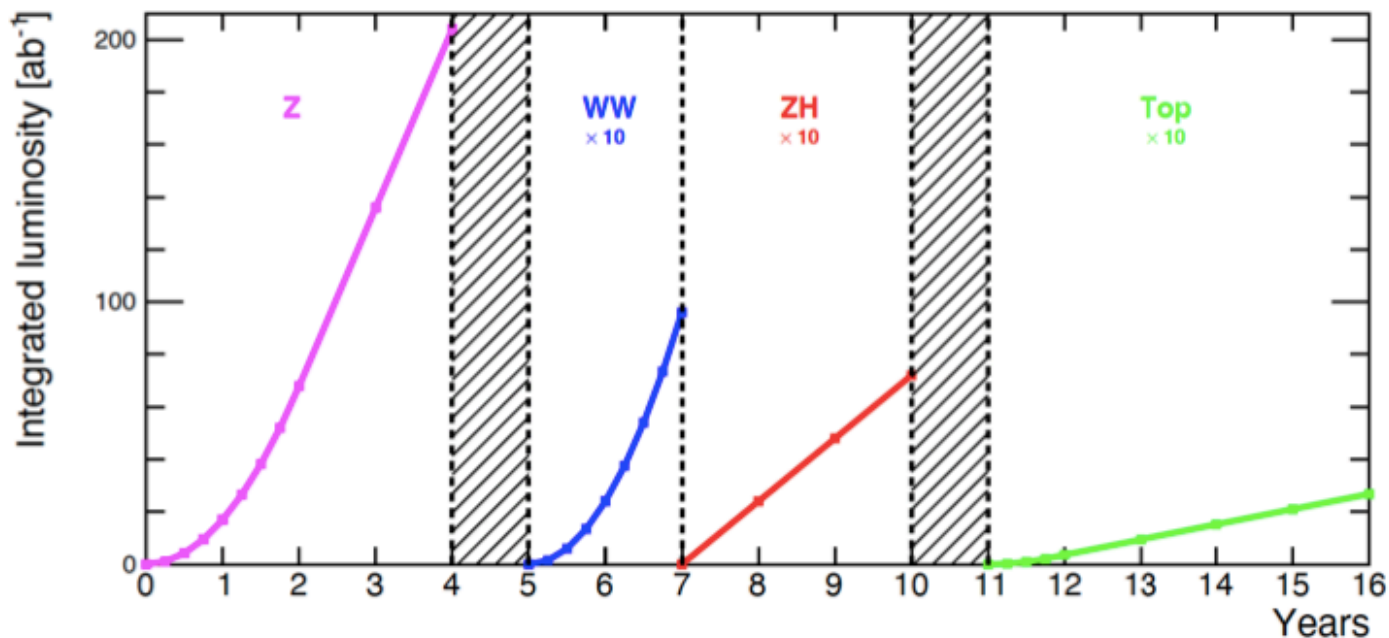
FCC feasibility Mid-term report - Physics and Experiments

FCC

- Baseline:
  - Flexibility is key, e.g. one year at the *Z* pole, installation of RF, one year for *WW*, then full *ZH* program, …

FCC

• Racetrack placement and democratic reach-out:

Optimized placement and layout for feasibility study

Major achievement: optimization of the ring placement

Layout chosen out of ~ 100 initial variants, based on geology and surface constraints (land availability, access to roads, etc.), environment (protected zones), infrastructure (water, electricity, transport), etc. "Éviter, reduire, compenser" principle of EU and French regulations

Lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold superperiodicity, possibility of 2 or 4 IPs

Whole project now adapted to this placement

V. Mertens, J. Gutleber
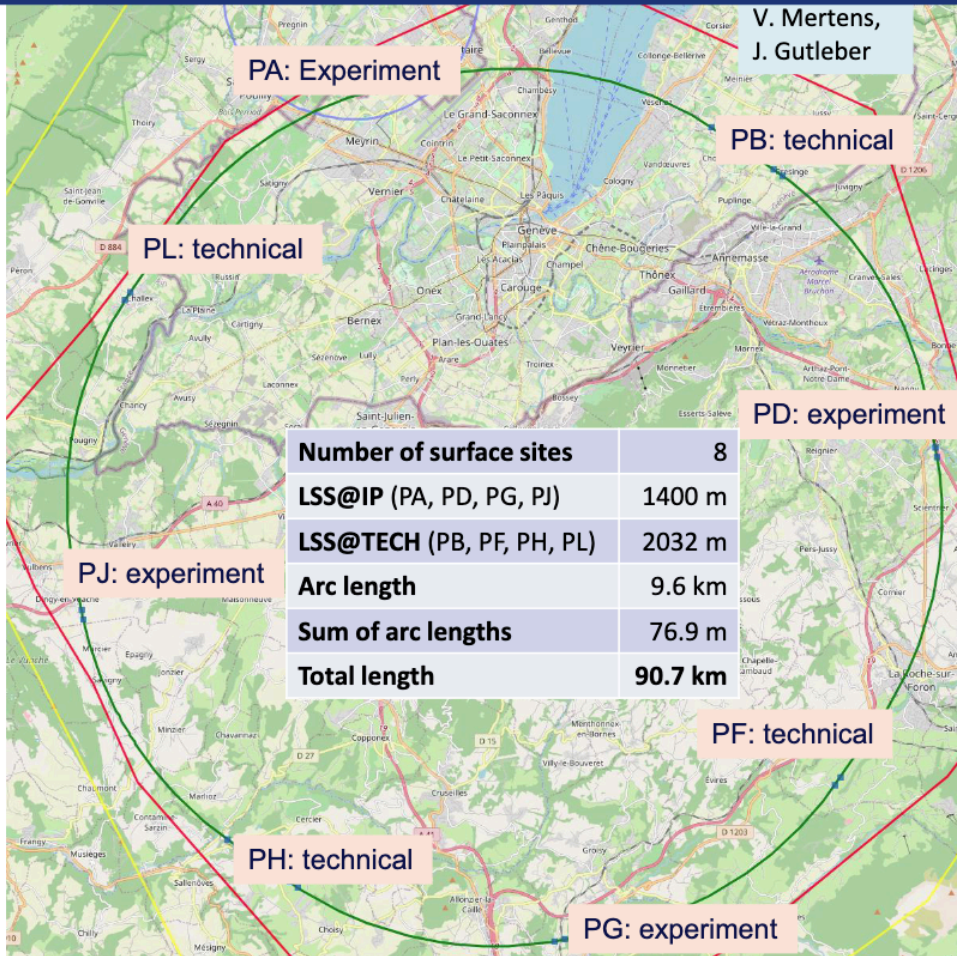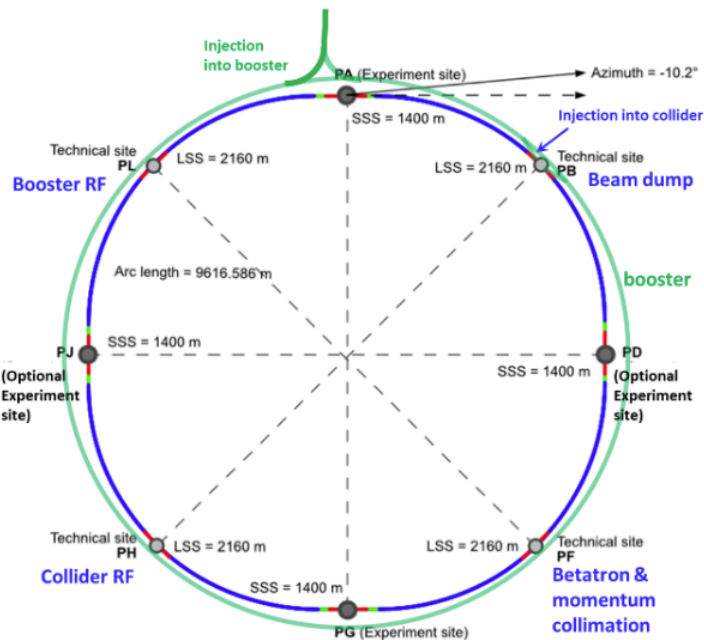
PA: Experiment
PB: technical
PL: technical
PD: experiment
PJ: experiment
PF: technical
PH: technical
PG: experiment

Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	90.7 km

- Racetrack placement and democratic reach-out: © J. Gutleber

FUTURE CIRCULAR COLLIDER

implementation baseline PA31   90.7 km

Meetings with municipalities concerned in France (31) and Switzerland (10)

PA – **Ferney Voltaire** (FR) – site experimental

PB – **Présinge/Choulex** (CH) – site technique

PD – **Nangy** (FR) – site technique et experimental

PF – **Roche sur Foron/Etaux** (FR) – site technique

PG – **Charvonnex/Groisy** (FR) – site experimental

PH – **Cercier** (FR) – site technique

PJ – **Vulbens/Dingy en Vuache** (FR) site technique et experimental

PL – **Challex (FR) – site technique**

Rencontrée individuellement

Rendez-vous proposé / programmé

Rencontre collective

Environmental studies and preparation of geological investigations (drillings and seismics) ongoing since February 2023
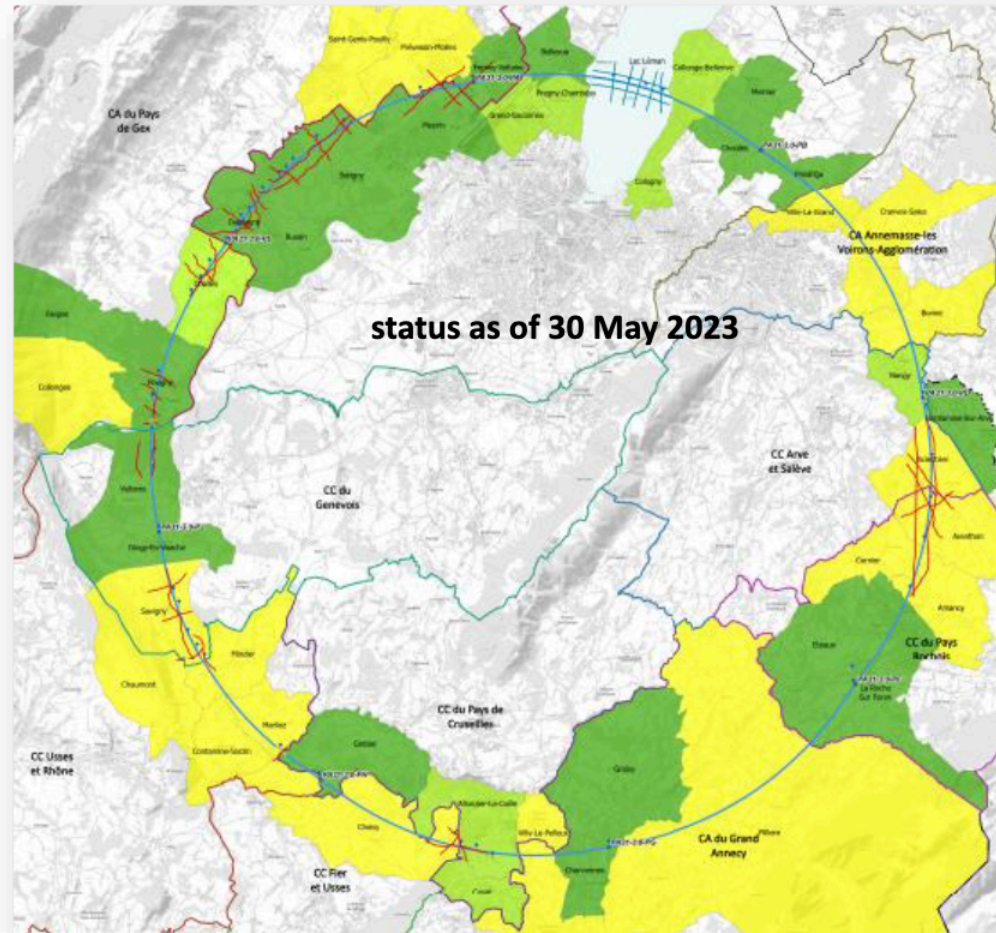
status as of 30 May 2023

- Racetrack placement and democratic reach-out: (as of january 2024)
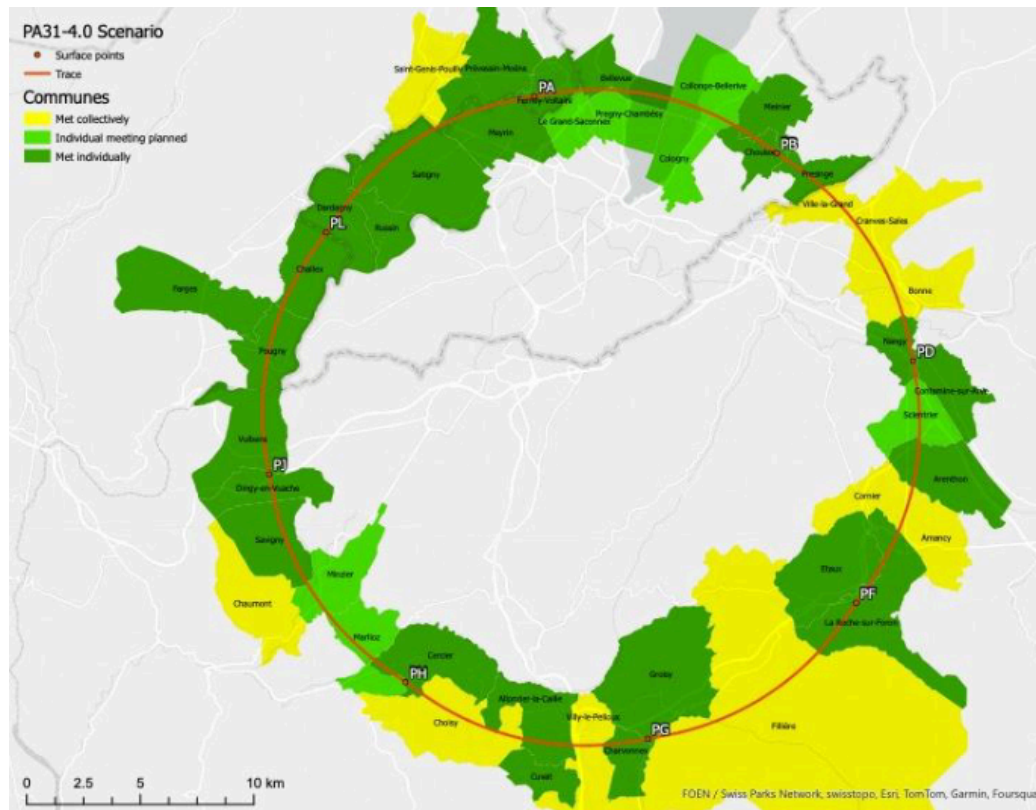
- Message#1: the machine design is matured as underlined by the mid-term review.

- Message#2: this schedule is (imo) the only conservative schedule of the projects on the market. Can be felt discouraging but realistically solid.

FCC

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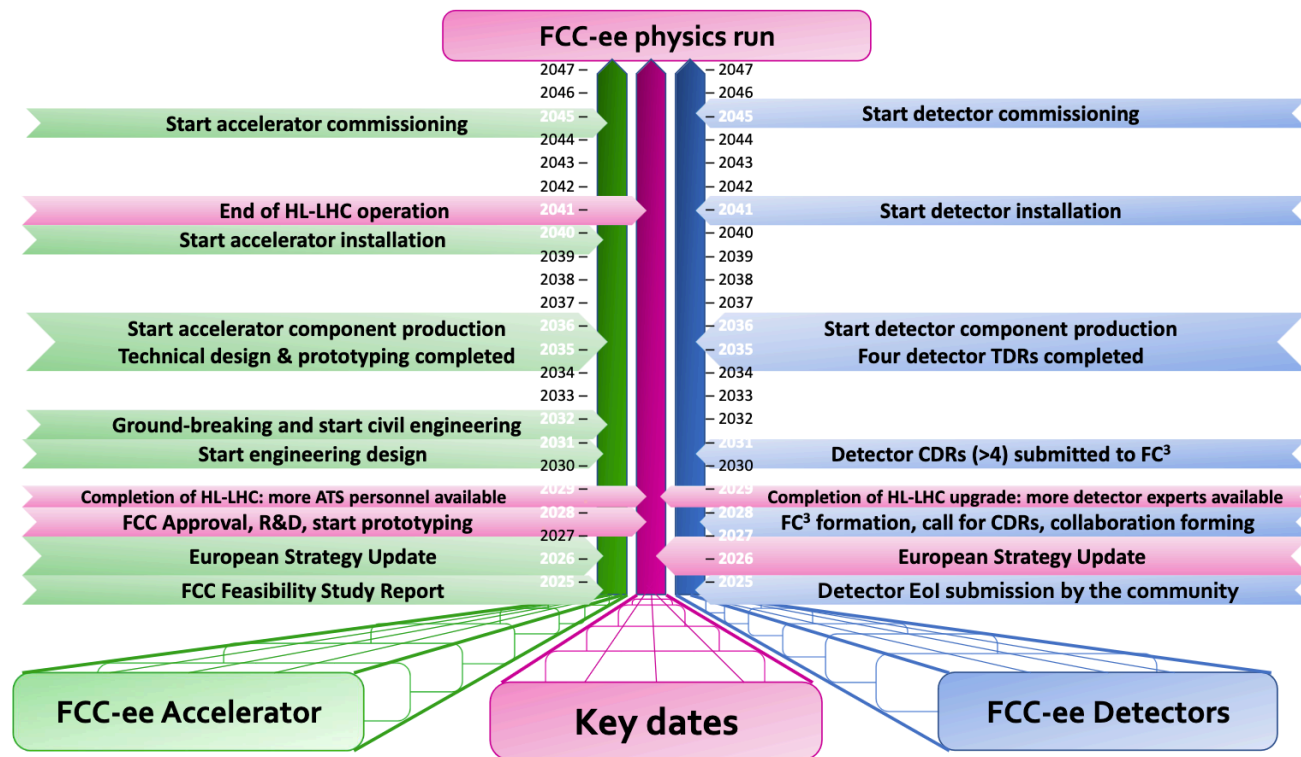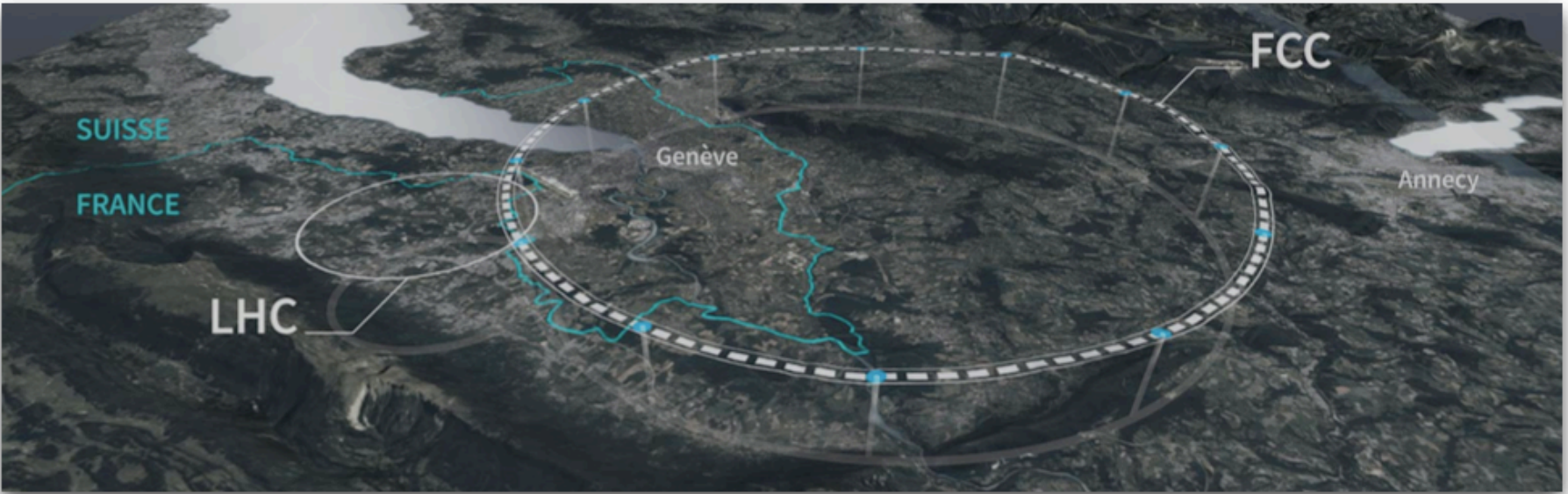
Z pole

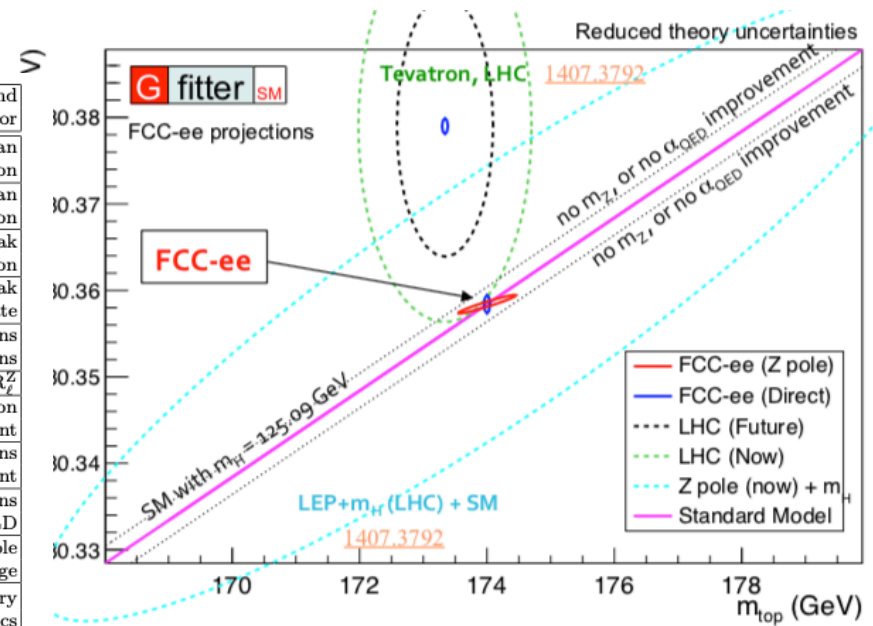**tt thr.** **WW thr.**

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\mathrm{eff}}(\times 10^6)$	231480 ± 160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\mathrm{QED}}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
$R_\ell^Z (\times 10^3)$	20767 ± 25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	From R_ℓ^Z
$\sigma_{\mathrm{had}}^0 (\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
$R_b (\times 10^6)$	216290 ± 660	**0.3**	< 60	Ratio of bb to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0 (\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{\mathrm{pol},\tau} (\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	Momentum scale
τ leptonic ($\mu\nu_\mu\nu_\tau$) B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010 ± 270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\mathrm{top}}/\lambda_{\mathrm{top}}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	**0.5 − 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

- Ultimate quantum completeness consistency test of the SM.

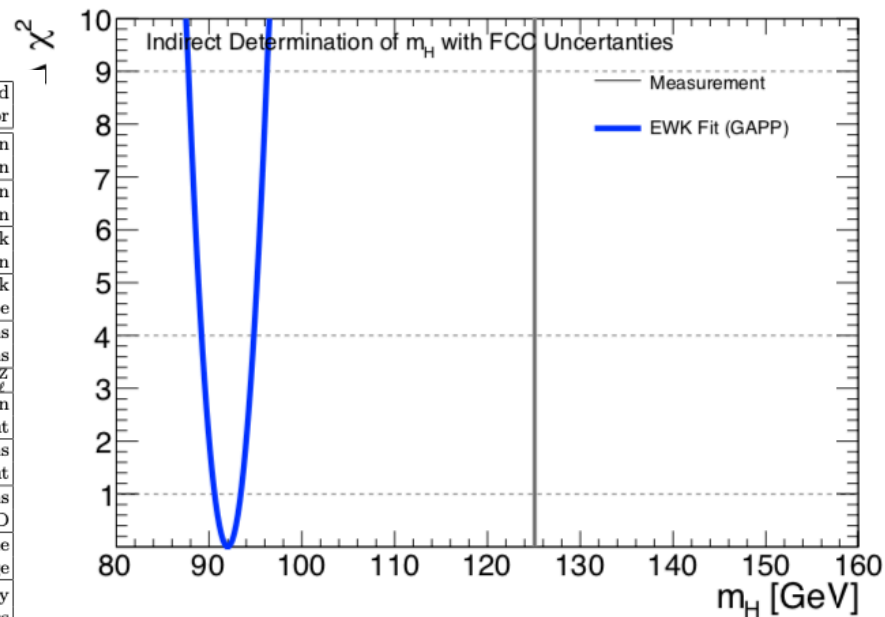- The improvements in theory prediction precision is part of the FCC program.

Z pole · **WW thr.** · **tt thr.**

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Indirect Determination of m_H with FCC Uncertainties — Measurement; EWK Fit (GAPP). χ^2 vs m_H [GeV].
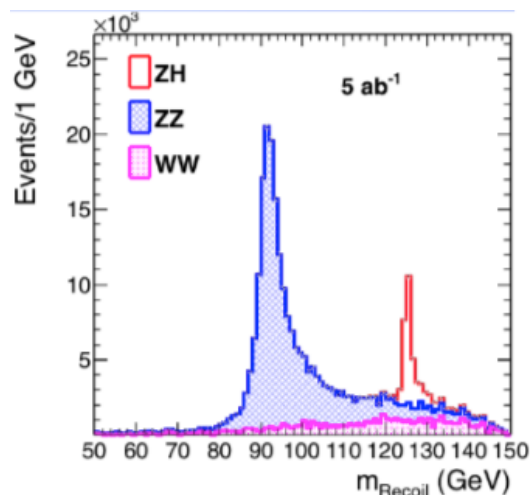
- Ultimate quantum completeness consistency test of the SM.

- The improvements in theory prediction precision is part of the FCC program. Precision 1.4 GeV.

- Two energy points (240 and 360 GeV) for the program
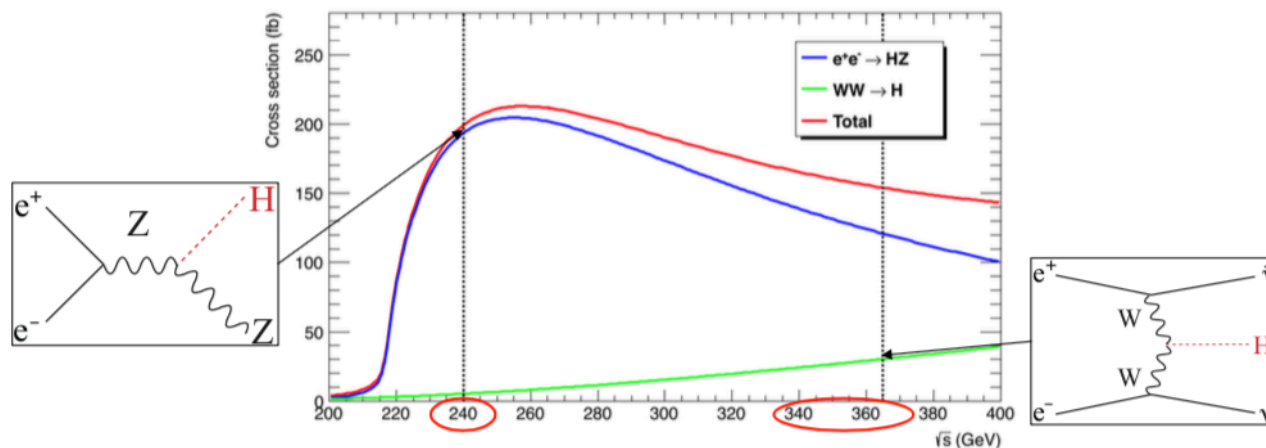
- Invincible precision on the absolute couplings and width. Interplay with HL-LHC.

Collider	HL-LHC	FCC-ee		
Luminosity (ab⁻¹)	3	5 @ 240GeV	+1.5 @ 365GeV	+HL-LHC
Years	25	3	+4	-
$\delta\Gamma_H/\Gamma_H$ (%)	SM	2.7	1.3	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.2	0.17	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.3	0.43	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.3	0.61	0.55
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	1.7	1.21	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	1.6	1.01	0.83
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.4	0.74	0.64
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	10.1	9.0	3.9
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	4.8	3.9	1.1
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	2.4
BR$_{EXO}$ (%)	SM (0.0)	<1.2	<1.0	<1.0

Results as in the CDR 2018

- It is interesting to note that the extrapolations provided for the CDR have mostly received confirmation from the latest studies, featuring more realistic detectors

Parameter	FCC-ee CDR	FCCee today
H→WW	1 %	2.0 %
H→ZZ	3.6 %	4.6 %
H→gg	1.6 %	0.78 %
H→γγ	7.5 %	3.5 %
H→cc	1.8 %	1.6 %
H→bb	0.25 %	0.18 %
H→μμ	15.8 %	19.5 %
H→ττ	0.75 %	0.9%
H→Zγ		
H→ss	–	103 %
Invisible	< 0.25 %	< 0.18 %
m_H	5 MeV	4 MeV
Γ_H	1 %	4%
κ_λ	42 %	30%

© J. Eysermans, as was shown end of january 2024.
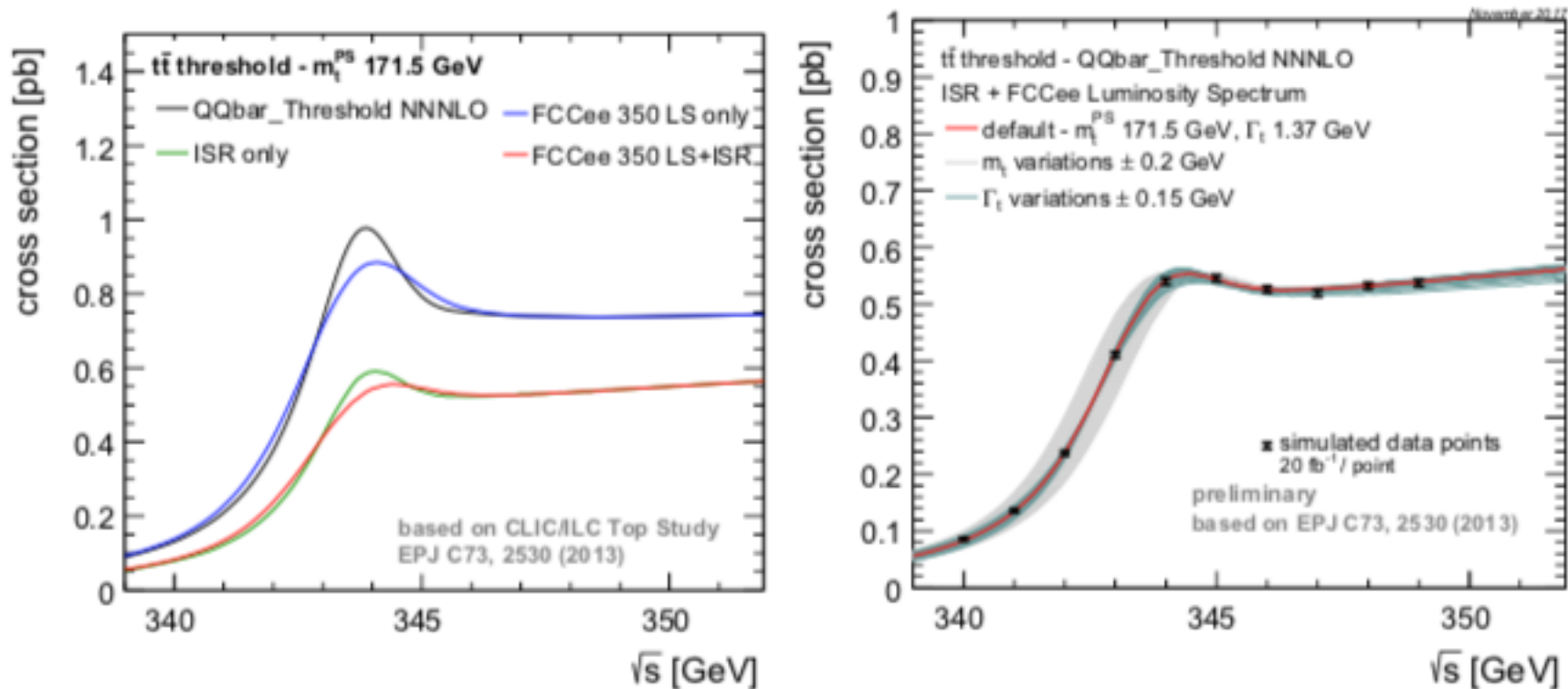
- Can get the top quark mass at the level of 20 MeV. Top width at 50 MeV.

© D. D'Enterria

Future: Permille uncertainty possible only with a machine like **FCC-e⁺e⁻**
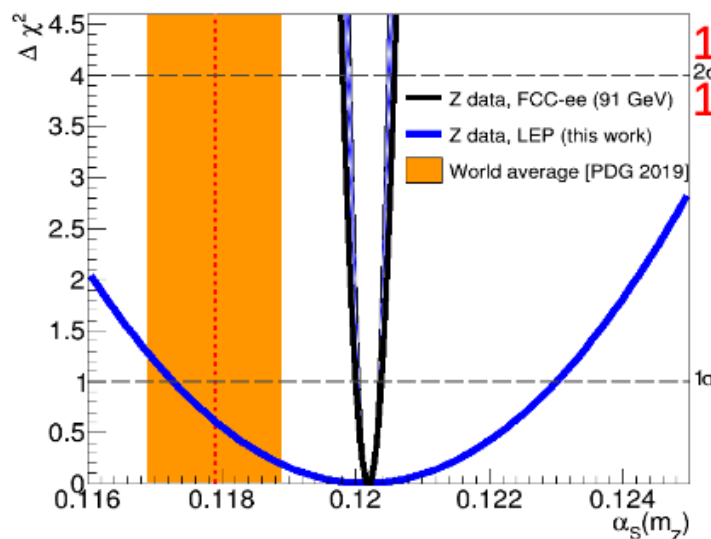
10^{12} **Z bosons**
10^{-5} syst. uncerts.

Strong SM
"stress test"
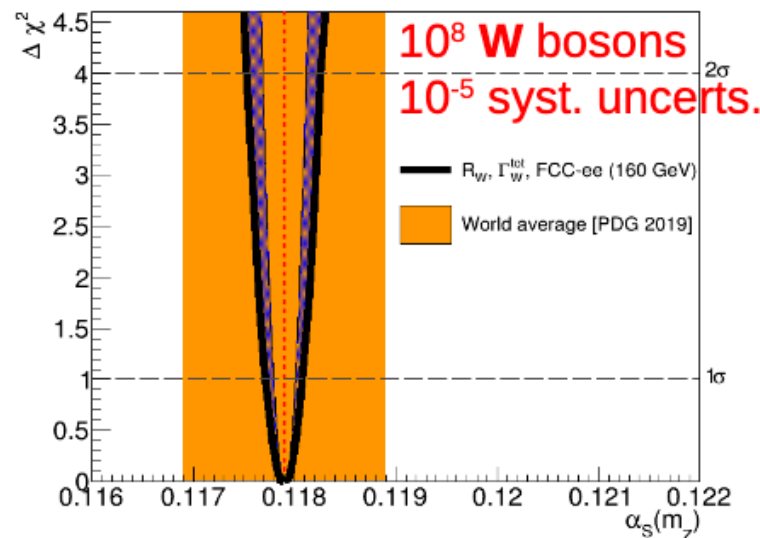
10^8 **W bosons**
10^{-5} syst. uncerts.

$\alpha_s(m_z) = 0.12030 \pm 0.00028 \pm 0.2\%$ (tot), $\pm 0.1\%$ (exp)

$\alpha_s(m_z) = 0.11790 \pm 0.00023 \pm 0.2\%$ (tot), $\pm 0.1\%$ (exp)

- The prospects for the strong coupling constant at Z and WW its width.

- Much more than what I'm flashing here for Heavy Neutral Leptons. Full program feature Axion-like Particles, dark sectors etc…
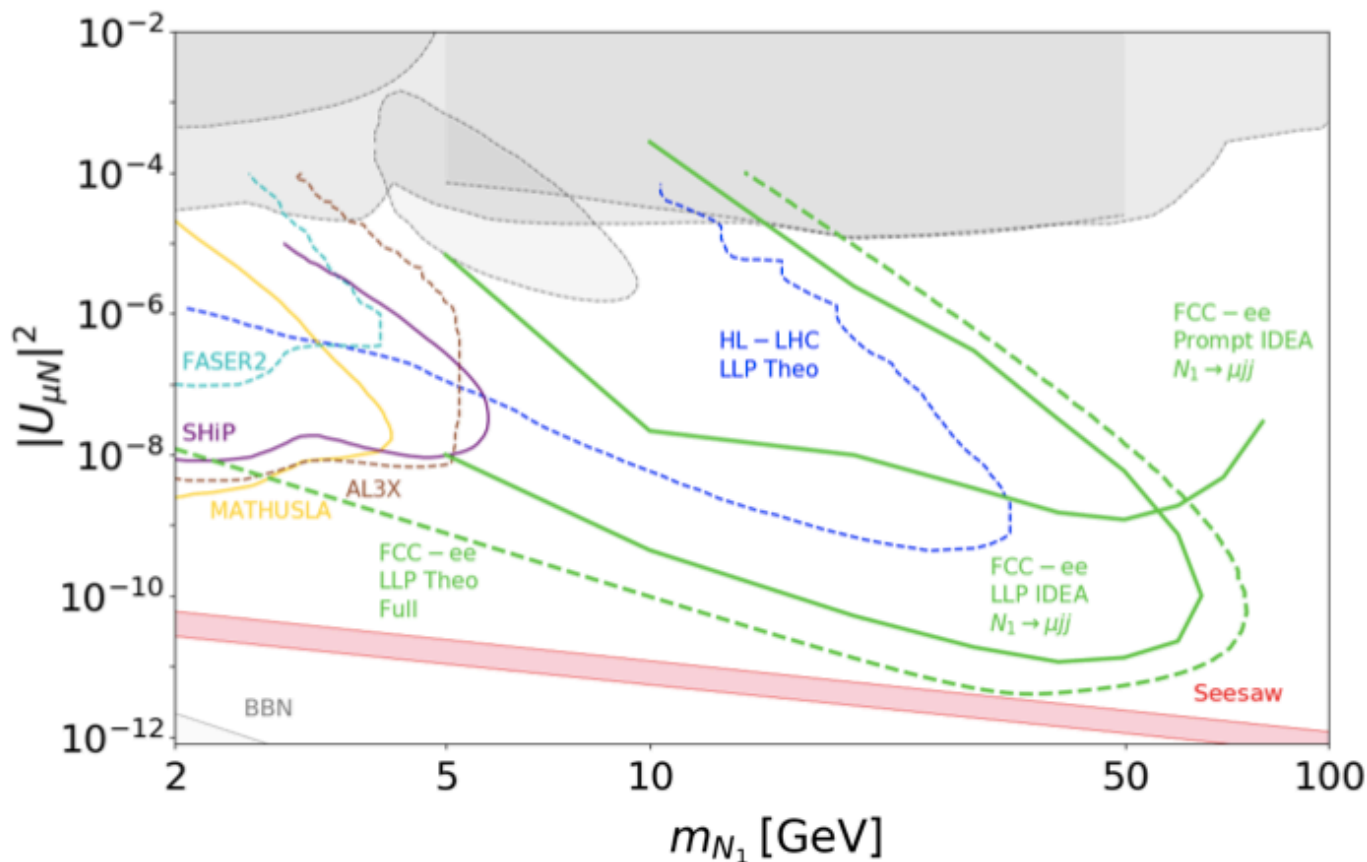
3. The Physics Case at large: discovery potential

- The Z pole can be a rich factory of Lepton Flavour violation processes. We'll see later for the tau lepton.

- Lepton Flavour-Violating *Z* decays in the SM with lepton mixing are typically $< 10^{-50}$.

- Any observation of such a decay would be an indisputable evidence for New Physics. FCC-*ee* exploration [JHEP 1504 (2015) 051]. $Z \to \tau\mu/e$ is unique at FCC.

- The dominant background is $(Z \to \tau\tau)$, where one tau decays into a close to beam energy lepton. The search is limited by the momentum resolution. A lot of phenomenology to explore yet.

Legend:
- bckg: $Z \to \tau\tau$, with $\tau \to l\nu\nu$
- signal: $Z \to \tau l$

y-axis: events / 0.002 ($\times 10^3$)
x-axis: $x_l = p_l / p_{beam}$
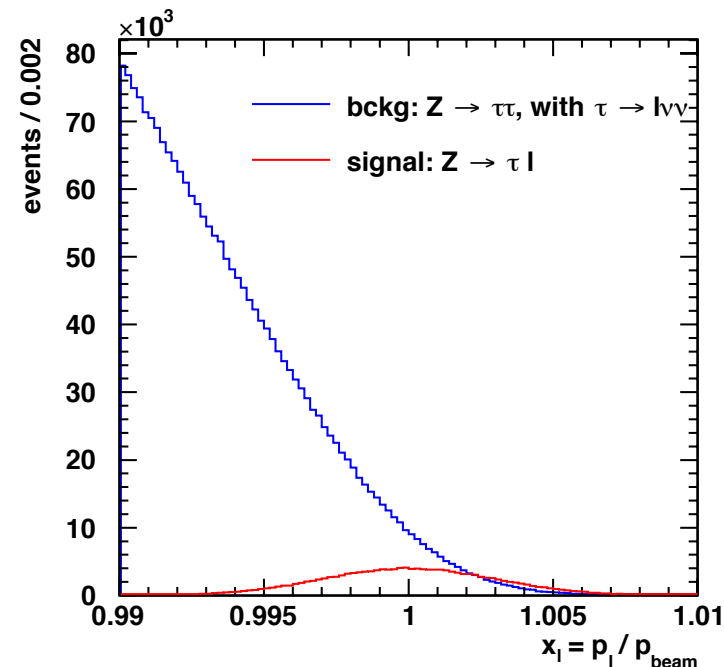
Bottomline: With the expected tracking performance at FCC-*ee* (beam spread equivalent resolution at 45 GeV), the current limits are pushed by three orders of magnitude, *e.g.* $O(10^{-9} - 10^{-10})$.

3. The Physics Case at large: detector concepts

- The physics reach is obviously intimately related to the detector performance

- So far three detector concepts defined by calorimetry

CLD
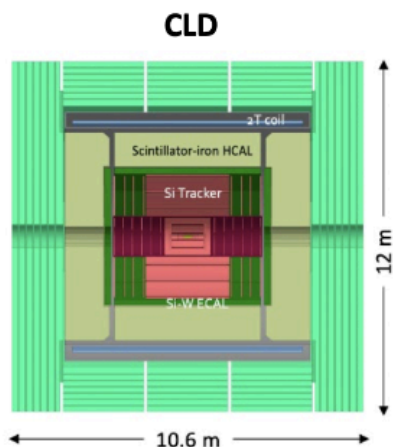
- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}(10$ ps) timing and/or RICH)?

IDEA
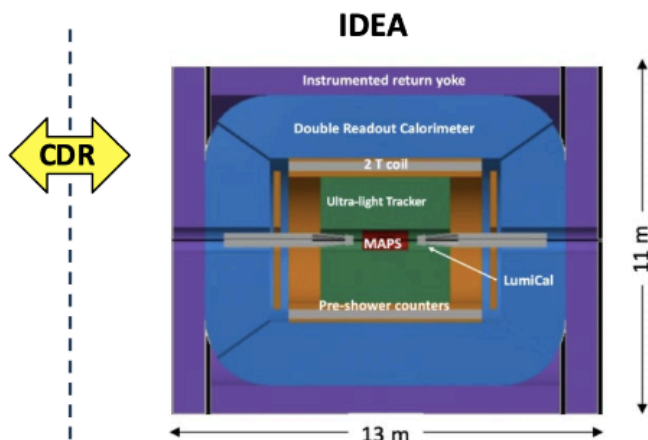
- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber with powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, ...

ALLEGRO

- The "new kid on the block"
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, ...
  - Software & performance studies
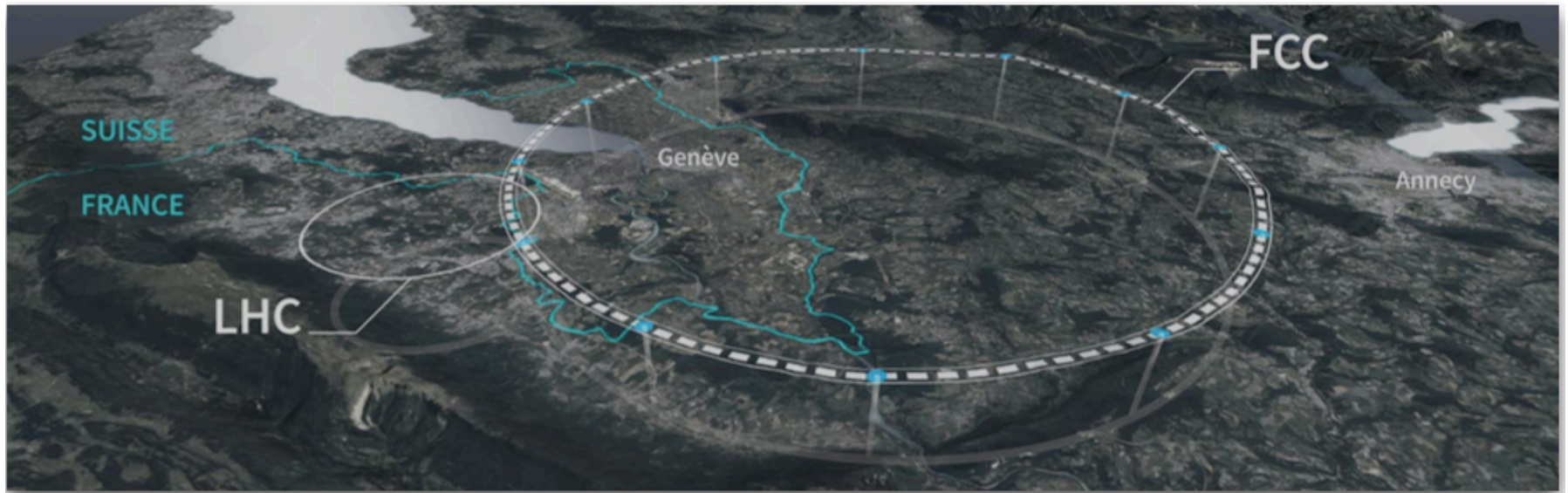
A- Particle production at the *Z* pole:

- About 15 times the nominal Belle II anticipated statistics for B^0 and B^+.
- All species of *b*-hadrons are produced.

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^8 WW		1.45×10^6 ZH + 45k WW → H	1.9×10^6 $t\bar{t}$ +330k ZH +80k WW → H	

Particle species	B^0	B^-	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield (10^9)	740	740	180	160	3.6	720	200

Table 1: Particle abundances for $6 \cdot 10^{12}$ Z decays. Charge conjugation is implied.

B- The Boost at the *Z*: $\langle E_{X_b} \rangle = 75\% \times E_{\text{beam}}; \langle \beta\gamma \rangle \sim 6.$

- Fragmentation of the *b*-quark:
- Makes possible a topological rec. of the decays w/ miss. energy.

C- Versatility : the *Z* pole does not saturate all Flavour possibilities. Beyond the obvious flavour-violating Higgs and top decays, the *WW* operation will enable to collect several 10^8 *W* decays on-shell AND boosted. Direct access to CKM matrix elements.

D- Comparison w/ LHC and B-factory. Advantageous attributes:

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

D- Comparison w/ LHC and B-factory. Advantageous attributes:

Important note: there's a hole in this table. The Heavy Quarks production at the LHC is invincible. The exquisite luminosity at the Z pole mitigates this LHC(b) advantageous attribute to a certain extent. Yet, the statistics at play for fully charged modes is commensurate with those of LHCb-Upgrade II.

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

FCC

2106.01259

4) FCC-ee ABCD specifics for Flavour Physics.

Invariant-mass resolution is a must: exquisite tracking is necessary and at reach. Invariant-mass resolution as it is in the current state of IDEA fast simulation:

2106.01259
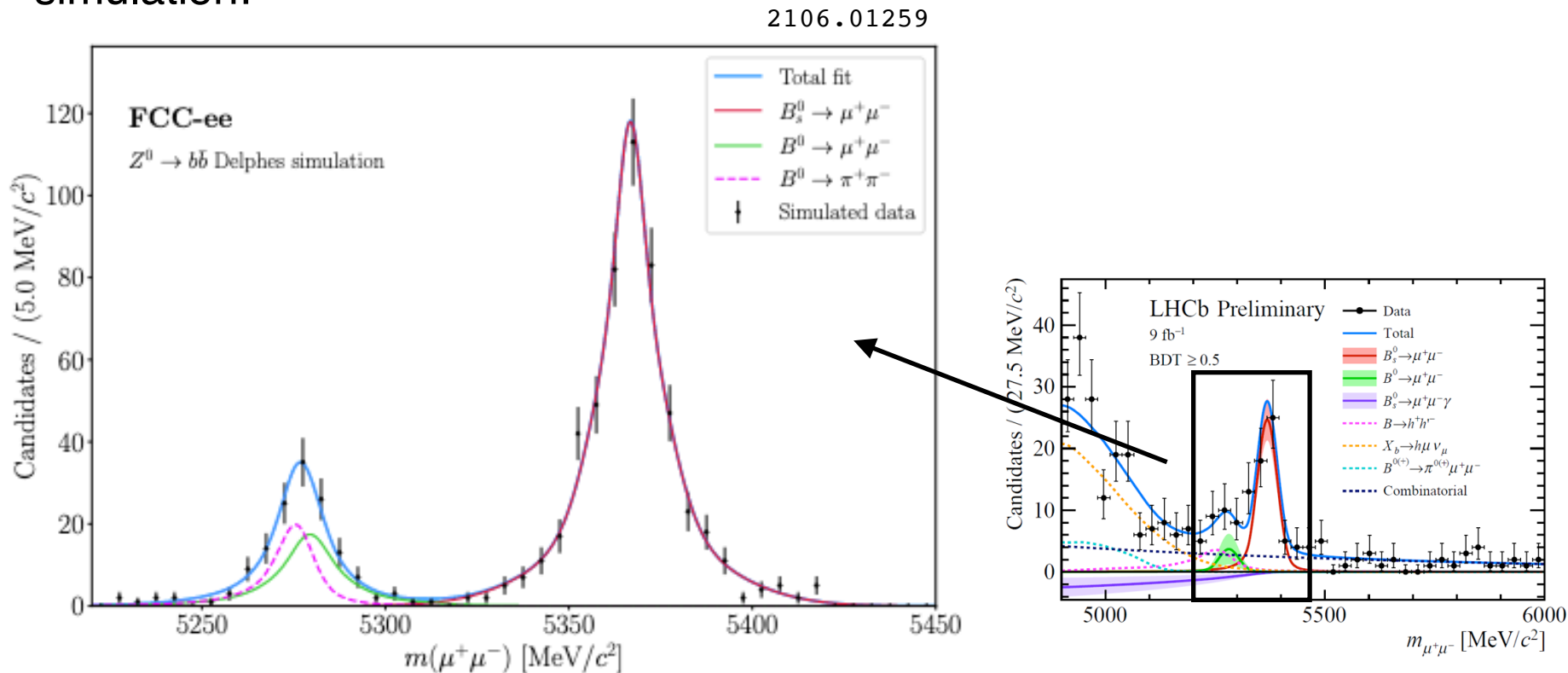
Seems granted w/ state-of-the-art tracker. Ultra-high resolution calorimetry is in addition desirable to touch high performance for modes w/ neutrals

Final remarks on this section -

Advantageous attributes / detector requirements

- The boost of the Z makes the b-flavoured (tau) particles fly ~3 (2) mm on average. Flavour Physics successful if those are resolved with high precision in particular when the mom. of the tracks is low
—> go beyond the state-of-the art.
- *CP* violation studies requires excellent K_S and neutral pions reconstruction. In order to make full advantage of the available statistics, exquisite energy and angular reconstruction in calorimetry
—> go beyond the state-of-the art.
- Hadronic *p* / *K* / *π* Particle IDentification has to come from the dE/dx (dN/dx) or a Cerenkov detector to fit in front of the ECAL
—> go beyond the state-of-the art.

Four IPs provide opportunities for a flavour-oriented detector concept.

FCC

- A look back:

  - The Flavour Program was not explored in the very-initial works about FCC-ee (but a mention to tau final states). It is now part of the program on its own right.

  - The case has to be thought of out of the anticipated very-rich experimental landscape at the horizon 2040 : there are LHCb Upgrade 2 (not yet approved but highly desirable — 300 /fb), Belle II (some thoughts about Belle III — 250 /ab) and Super Tau-Charm Factory (STCF).

  - The question was: is there a valuable addition to the Flavour physics case that will be developed in the next two decades?

  - The answer is: YES. Focus was put on the study of modes that are likely unique to FCC-ee. It happens in addition that there is no place where FCC-ee does not compete valuably, and hence provides at least a useful comparison.

- Rare semileptonic decays and leptonic decays:
  - $b \to s\tau^+\tau^-$, e.g. $B^0 \to K^{*0}\ \tau^+\tau^-$. (case for mid-term review)
  - $b \to s\nu\nu$, e.g. $B_s \to \phi\nu\nu$
  - $Bc \to \tau\nu$; $b \to s(d)\ \ell\ell$

- *CP* violation studies:
  - The CKM γ angle, e.g. $B_s \to D_sK$.
  - The semileptonic asymmetries (*CP* breaking in mixing).
  - The CKM α angle, e.g. $B^0 \to (\pi^0\pi^0)$.
  - The matrix elements V_{ub} and V_{cb} ….

- Tau Physics:
  - Lepton flavour violating τ decays
  - Lepton-universality tests in τ decays.

- Charm Physics:
  - The rare decays, e.g. $D \to \pi\nu\nu$, $D^0 \to \gamma\gamma$
  - The hadronic decays, $D^+ \to \pi^+\pi^0$ …

FCC

· Flashing some of the recent studies: $b \rightarrow s\nu\nu$
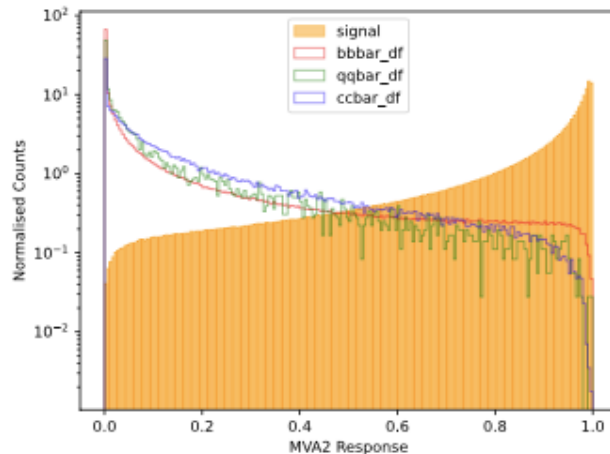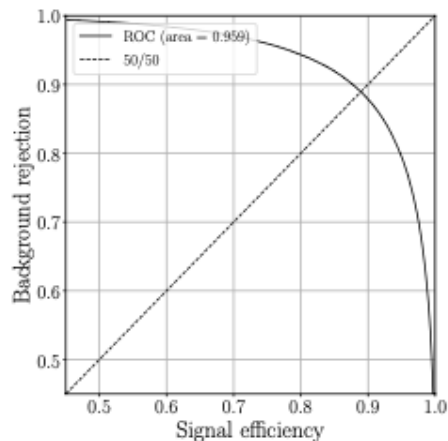
© A. Wiederhold, M. Kenzie
arXiv:2309.11353

$B_s^0 \rightarrow \phi\nu\bar{\nu}$ **Efficiency and Sensitivity**

First indication of such a transition just came from Belle II (2023).

Analysis based on the hemisphere missing energy measurement confronting the event properties.

For an optimal BDT1 and BDT2 cut at the SM predicted BF:

▶ Signal efficiency $\sim 11\%$
▶ $b\bar{b}$ efficiency $\sim 10^{-4}\%$
▶ $c\bar{c}$ efficiency $\sim 10^{-6}\%$
▶ $q\bar{q}$ efficiency $\sim 10^{-7}\%$
▶ Signal:Background ratio $\sim 1:9$
▶ Sensitivity $\sim 1.2\%$
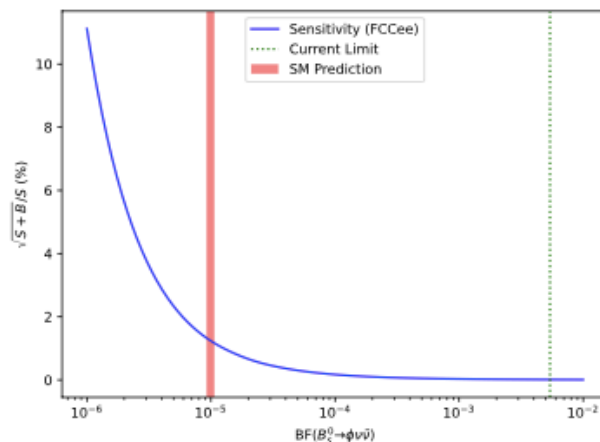
- $B_c \rightarrow \tau^+\nu$: another fundamental test of lepton universality. Counterpart of R_{D,D^*}. A promising study lies here [2105.13330, see also 2007.08234]

FCC-ee Simulation (IDEA Delphes)

(a)

Generated data
Total fit
$B_c^+ \rightarrow \tau^+\nu_\tau$
$B^+ \rightarrow \tau^+\nu_\tau$
Background

Candidates / (1.0 GeV/c^2)

Maximum hemisphere E [GeV/c^2]

FCC-ee Simulation (IDEA Delphes)

(b)

$B(B_c^+ \rightarrow \tau^+\nu_\tau)$ relative σ

$N_Z(\times 10^{12})$
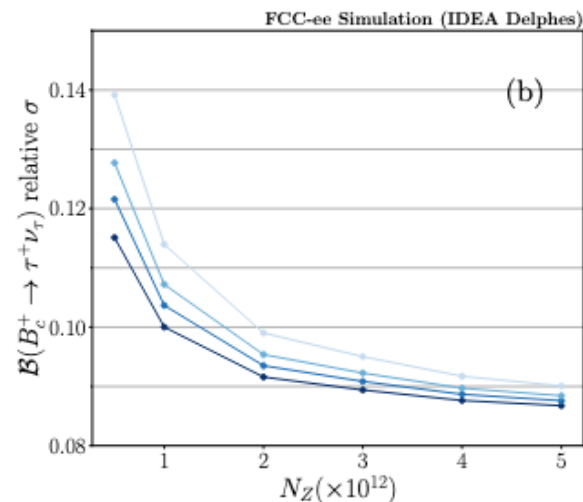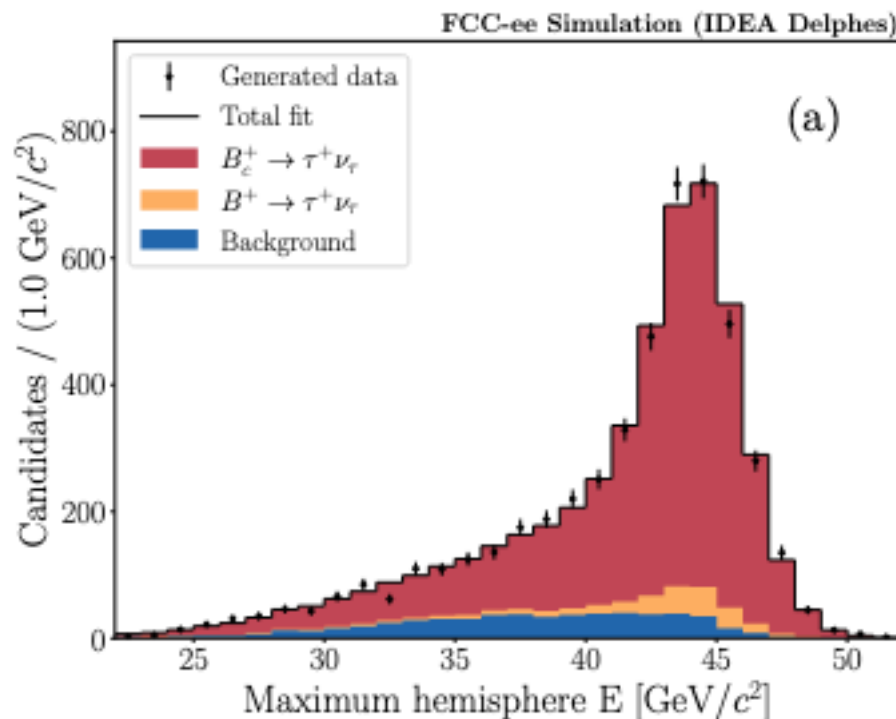
© X. Zuo et al.

Bottomline: few percent precision mostly limited yet by the knowledge of the normalisation BF (J/$\psi\mu\nu$).

- $B^+ \to \tau^+ \nu$: access $|V_{ub}|$ with the only knowledge of the decay constant.
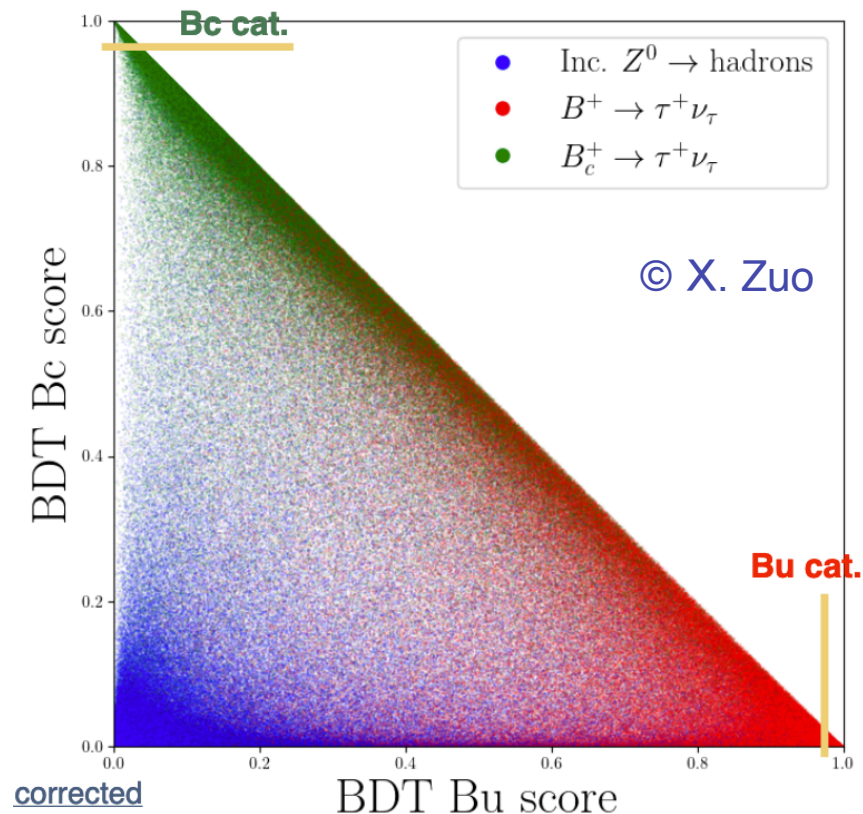
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Bottomline: similar yields / purities as for $B_c \to \tau^+ \nu$. A paper out. *arXiv 2305.02998* that makes the synthesis of both analyses.

- Sub-degree gamma angle measurement with just one mode :

Measurement of CP violation with $B_s \rightarrow D_s K$

$$\int Ldt = 150\ ab^{-1}$$

PDG: $\gamma = (71.1^{+4.6}_{-5.3})°$

© R. Aleksan

Result 3 :

$$\delta(\rho) \approx 3.2 \times 10^{-3}(stat.)$$

$$\delta(sin^2\phi_{CKM}) \approx \delta(sin^2\gamma) \approx 5 \times 10^{-3}(stat.) \cong \delta(\gamma) \approx 0.4°\ (stat.)$$
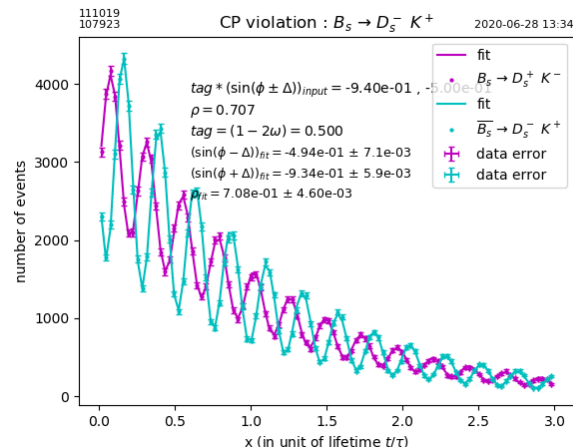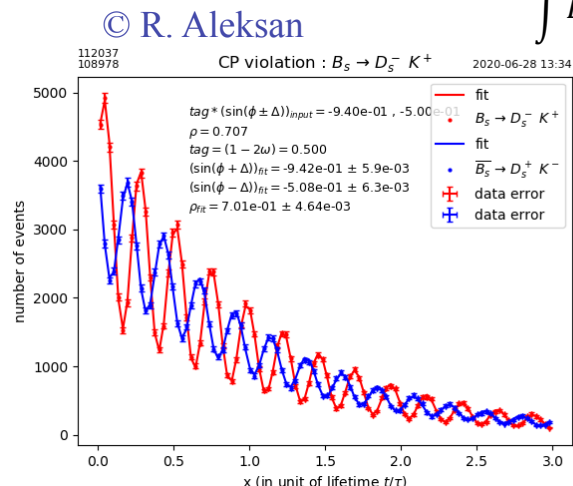
Potential statistical gain of factor 4-5 with $D_s^{\pm} \rightarrow K^{*0}K^{\pm}, \phi\rho^{\pm}, ...$ but background needs to be studied (see later)+
Additionnal potential gain (another factor ~2) with $B_s \rightarrow D_s^{*\pm}K^{\mp}, D_s^{\pm}K^{*\mp}, D_s^{*\pm}K^{*\mp}$, most modes including γ(s)

- A lot more to do with neutrals !
- Several null tests of the SM accessible w/ potentially unprecedented precision, *e.g.* semileptonic asymmetries, ϕ_s in penguin-dominated diagrams …

- Tau Physics: Lepton Flavour Universality

© A. Lusiani
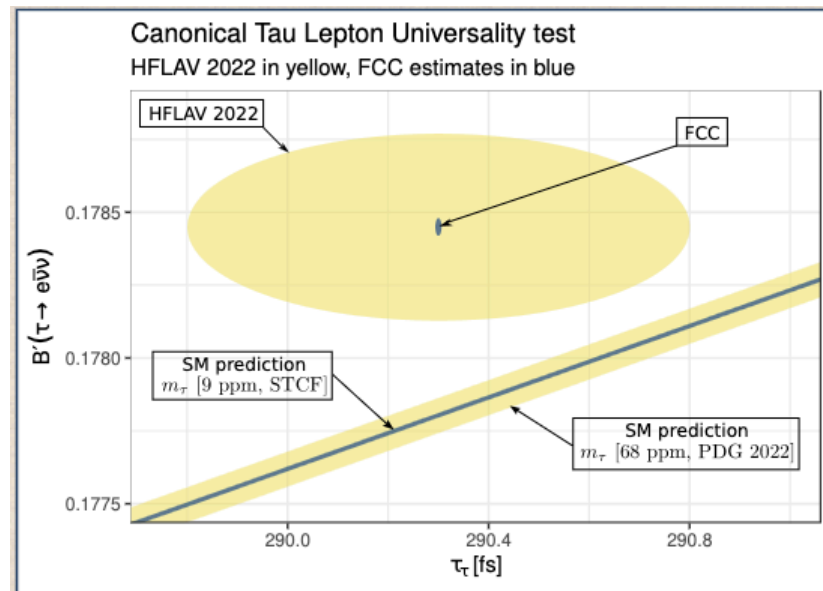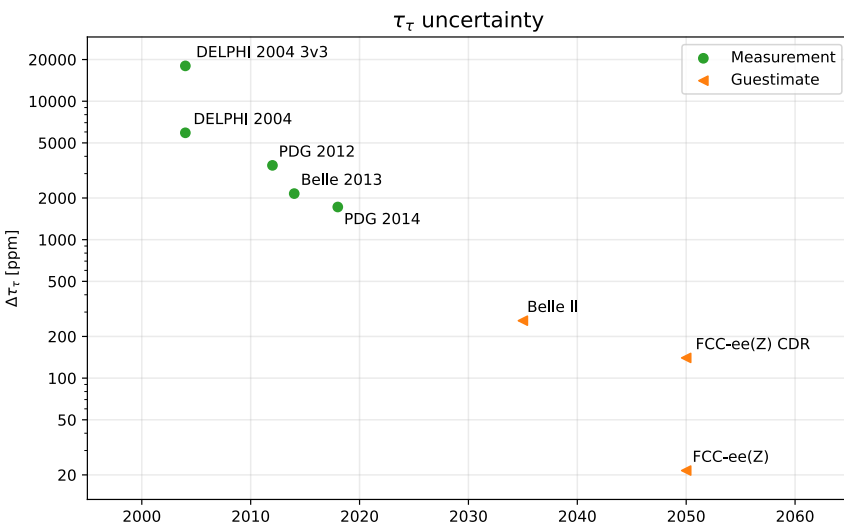
Comment: B-factories did not improve (much) LEP measurements (Belle II might). FCC-ee has much better experimental conditions than LEP and about 5× the statistics of tau pairs w.r.t. Belle II.
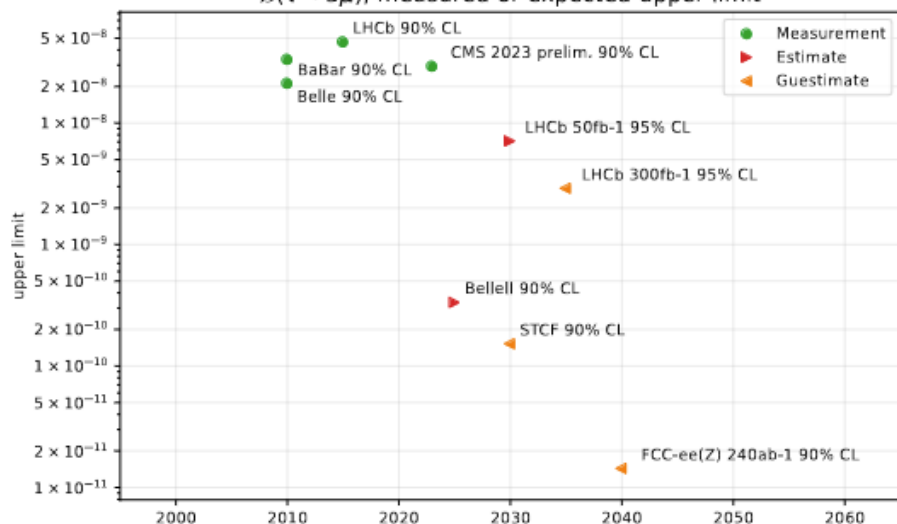
Bottomline: lifetime resolution obtained with three-prongs decays. Orders of magnitude improvements.

- Tau Physics: Lepton Flavour Violation

© A. Lusiani

$\mathcal{B}(\tau \to 3\mu)$, measured or expected upper limit

$\mathcal{B}(\tau \to \mu\gamma)$, measured or expected upper limit
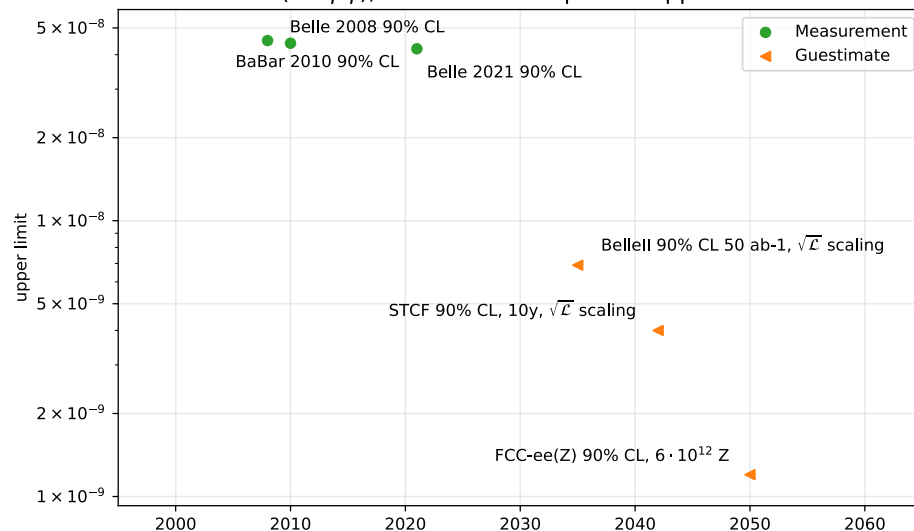
Bottomline: improved sensitivity by about two orders of magnitude.

FCC
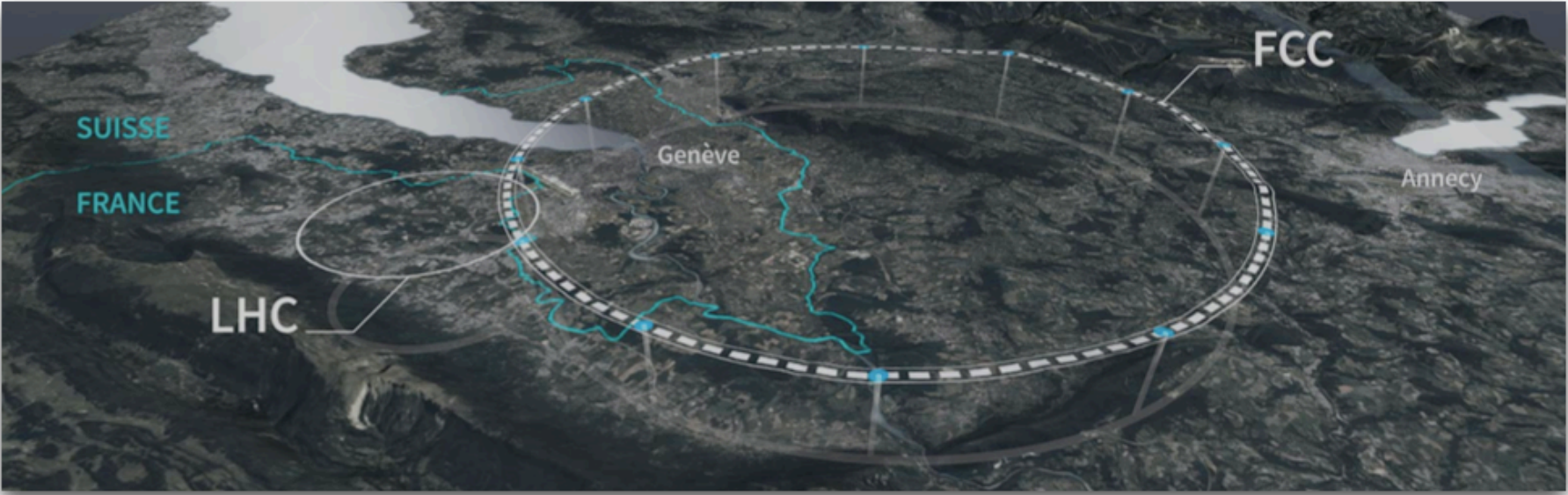
- At the horizon of the next electron collider, the knowledge of the CKM profile is expected to have been deeply revisited by LHCb and Belle II/III.

- The CKM angle γ might be known at the sub-degree precision; as will the angle β.

- One relevant figure of merit to devise the possible bottlenecks in precision that would alter the global interpretation of the CKM profile is a quasi-model-independent analysis of the BSM contributions in neutral kaon and beautiful-meson mixing phenomena.

- Bottomline: one needs the matrix element $|V_{cb}|$ at a much-higher precision than what semileptonic *B* decays can provide. The next couple of slides to justify the statement. $|V_{cb}|$ is the normalisation of the UT in the SM and beyond (in a large class of BSM models).

- Longstanding tensions in exclusive / inclusive determinations to be fixed!

- **Model-independent approach to constrain BSM Physics in neutral meson mixing processes**

$$\langle B_q \,|\, \mathcal{H}^{\mathrm{SM+NP}}_{\Delta B=2} \,|\, \bar{B}_q \rangle \equiv \langle B_q \,|\, \mathcal{H}^{\mathrm{SM}}_{\Delta B=2} \,|\, \bar{B}_q \rangle$$
$$\times \quad (\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q))$$

$$\mathrm{Re}(\Delta_q) + i\mathrm{Im}(\Delta_q) = r_q^2 e^{i2\theta_q} = 1 + h_q e^{i\sigma_q}$$

Soares & Wolfenstein, PRD 47, 1021 (1993)
Deshpande, Dutta & Oh, PRL77, 4499 (1996)
Silva & Wolfenstein, PRD 55, 5331 (1997)
Cohen et al., PRL78, 2300 (1997)
Grossman, Nir & Worah, PLB 407, 307 (1997)

<u>Assumptions:</u>

✓only the short distance part of the mixing processes might receive NP contributions.

✓Unitary 3x3 CKM matrix (Flavour violation only from the Yukawas-MFV hypothesis).

✓ tree-level processes are not affected by NP (so-called SM4FC: $b \to f_i f_j f_k$ ($i \neq j \neq k$)). As a consequence, the quantities which do not receive NP contributions in that scenario are:

$$|V_{ud}|, \ |V_{us}|, \ |V_{ub}|, \ |V_{cb}|, \ B^+ \to \tau^+ \nu_\tau \text{ and } \gamma$$

- The unitarity triangle parameters w/ |V...
  This is the anticip...
  Belle II and LHCb...
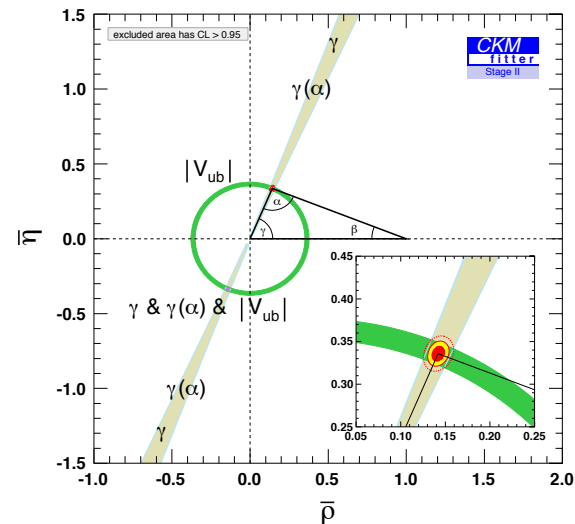
- Knowing the CKM parameters, one can introduce the constraints of the *B* mixing observables depending on the NP complex number (here parameterised as Δ).

parameter	prediction in the presence of NP
Δm_q	$|\Delta_q^{\mathrm{NP}}| \times \Delta m_q^{\mathrm{SM}}$
2β	$2\beta^{\mathrm{SM}} + \Phi_d^{\mathrm{NP}}$
$2\beta_s$	$2\beta_s^{\mathrm{SM}} - \Phi_s^{\mathrm{NP}}$
2α	$2(\pi - \beta^{\mathrm{SM}} - \gamma) - \Phi_d^{\mathrm{NP}}$
$\Phi_{12,q} = \mathrm{Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}}$
A_{SL}^q	$\frac{\Gamma_{12,q}}{M_{12,q}^{\mathrm{SM}}} \times \frac{\sin(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})}{|\Delta_q^{\mathrm{NP}}|}$
$\Delta\Gamma_q$	$2|\Gamma_{12,q}| \times \cos(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})$

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left(\frac{4.5\,\text{TeV}}{\Lambda}\right)^2,$$

$$\sigma = \arg\left(C_{ij}\,\lambda_{ij}^{t*}\right),$$
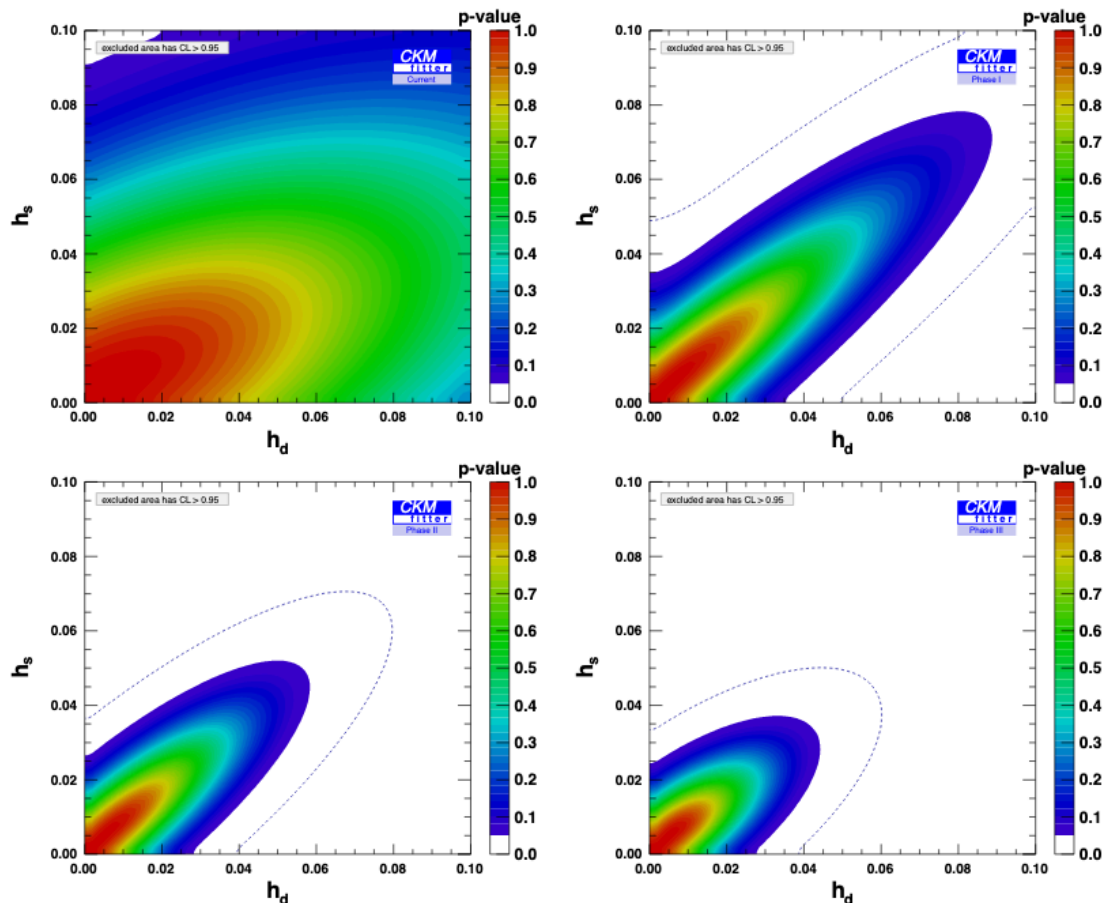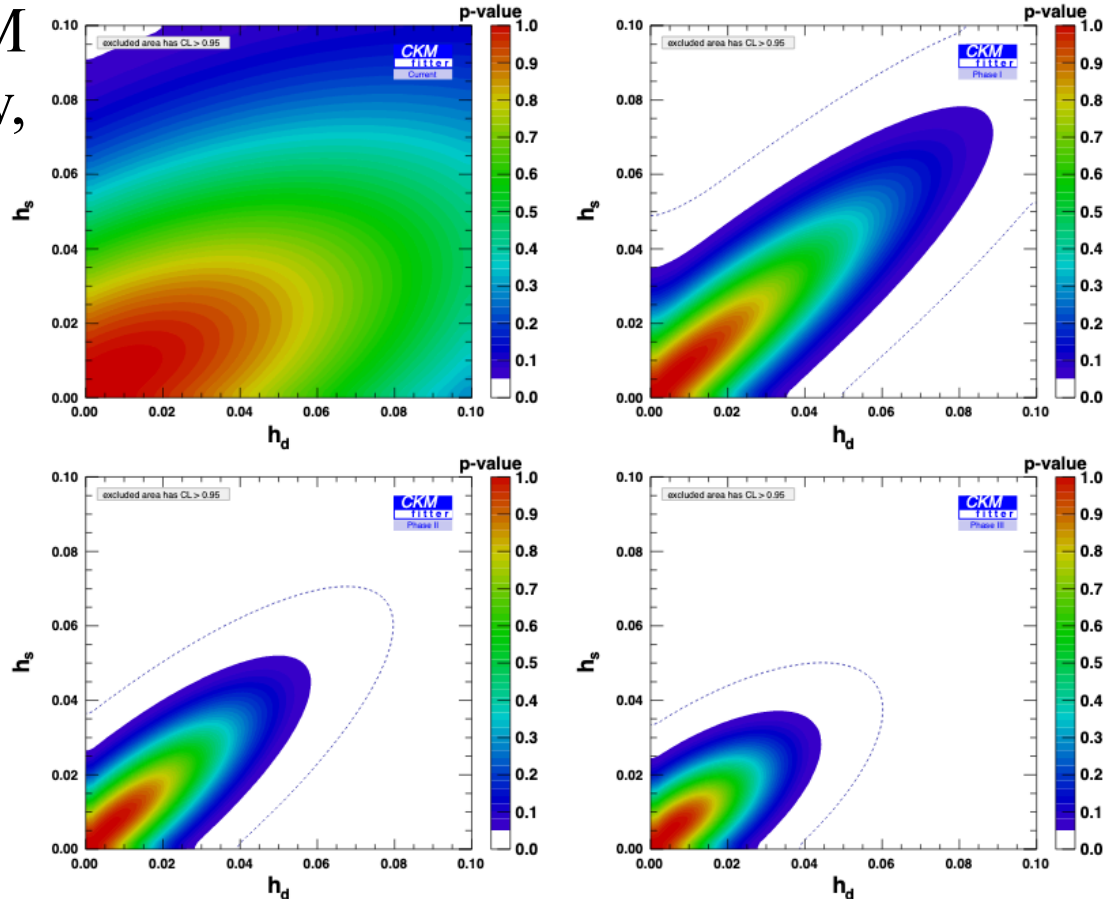
hep-ph 2006.04824

FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ) contours.

6) Focus#1: the CKM matrix element V$_{cb}$

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left(\frac{4.5\,\text{TeV}}{\Lambda}\right)^2,$$

$$\sigma = \arg\left(C_{ij}\,\lambda_{ij}^{t*}\right),$$

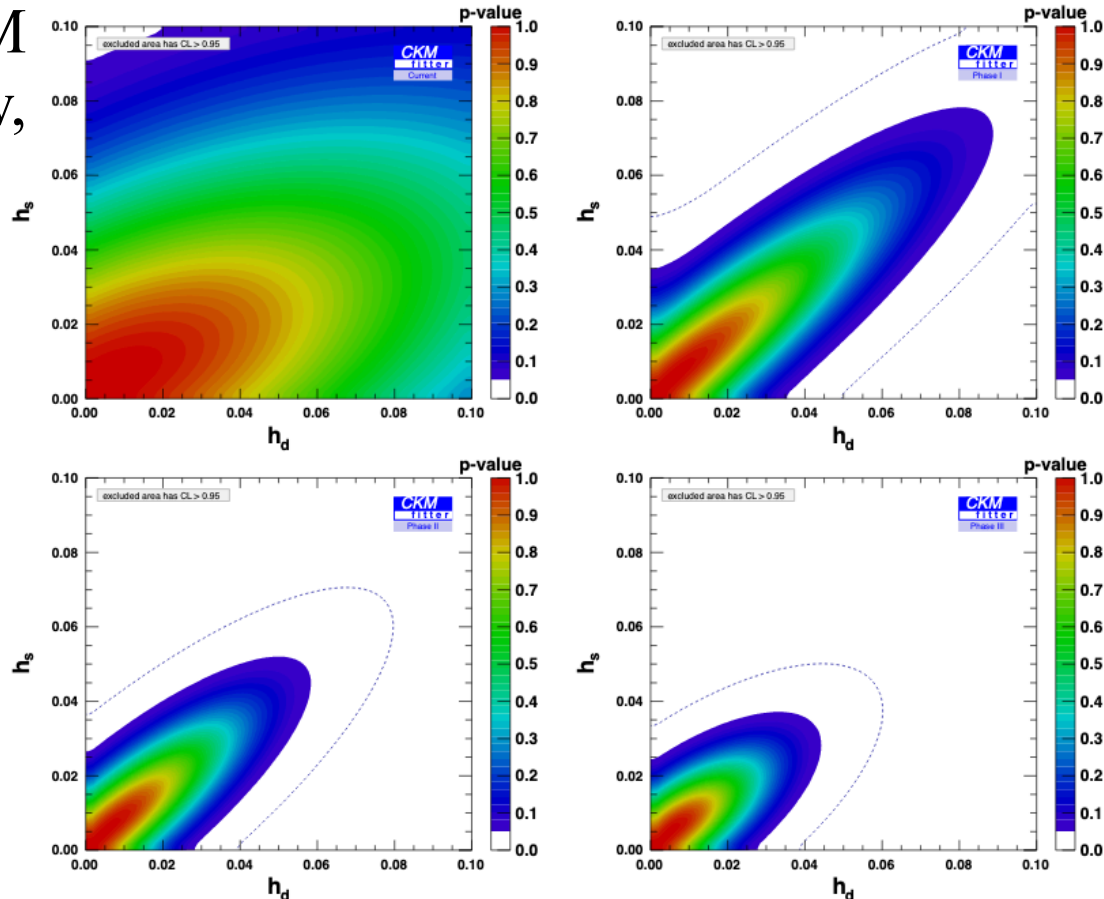hep-ph 2006.04824

rescaled to SM
— Now,

FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ) contours.

S. Monteil
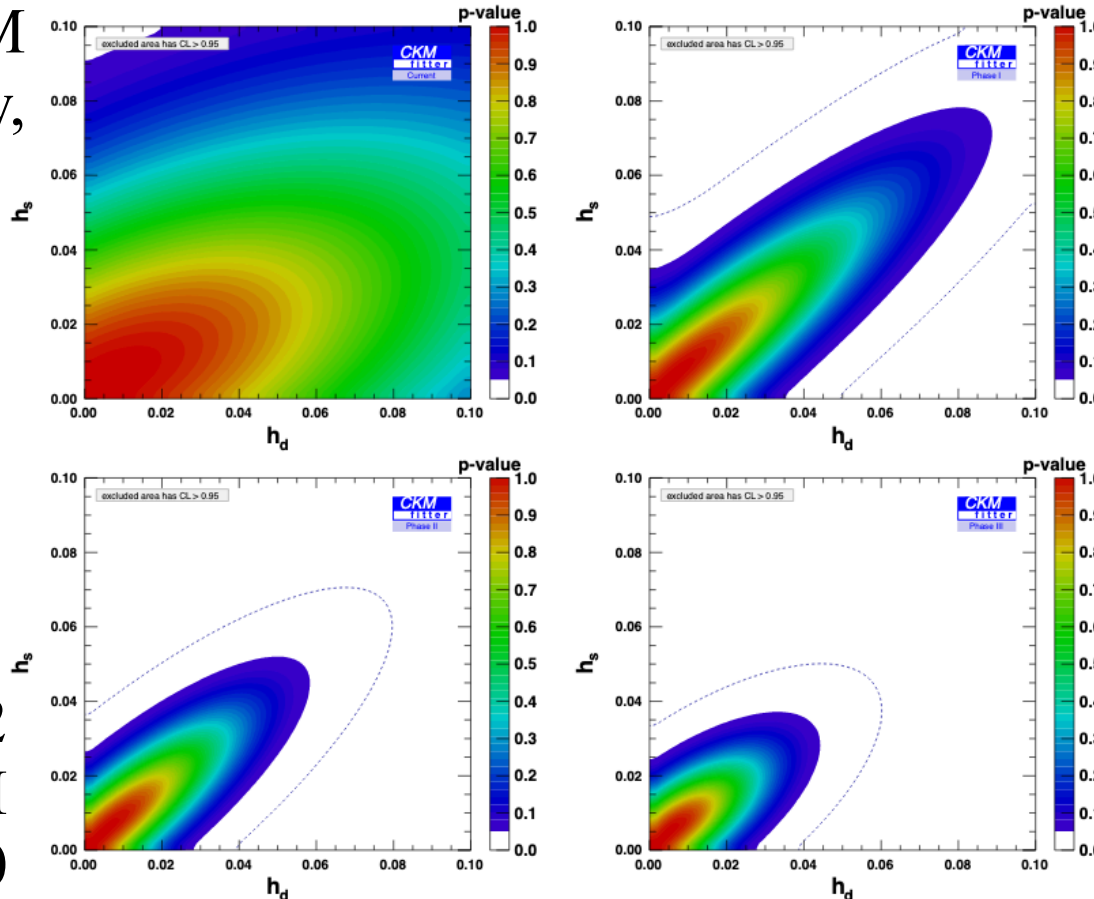
43

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left(\frac{4.5\,\mathrm{TeV}}{\Lambda}\right)^2,$$

$$\sigma = \arg\left(C_{ij}\,\lambda_{ij}^{t*}\right),$$

hep-ph 2006.04824

rescaled to SM
— Now,

after LHCb-U1
and Belle II
— 2030

FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ) contours.

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left(\frac{4.5\,\text{TeV}}{\Lambda}\right)^2,$$

$$\sigma = \arg\left(C_{ij}\,\lambda_{ij}^{t*}\right),$$

hep-ph 2006.04824

rescaled to SM — Now,

after LHCb-U1 and Belle II — 2030

after LHCb U2 and Belle III — 2040

FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ) contours.
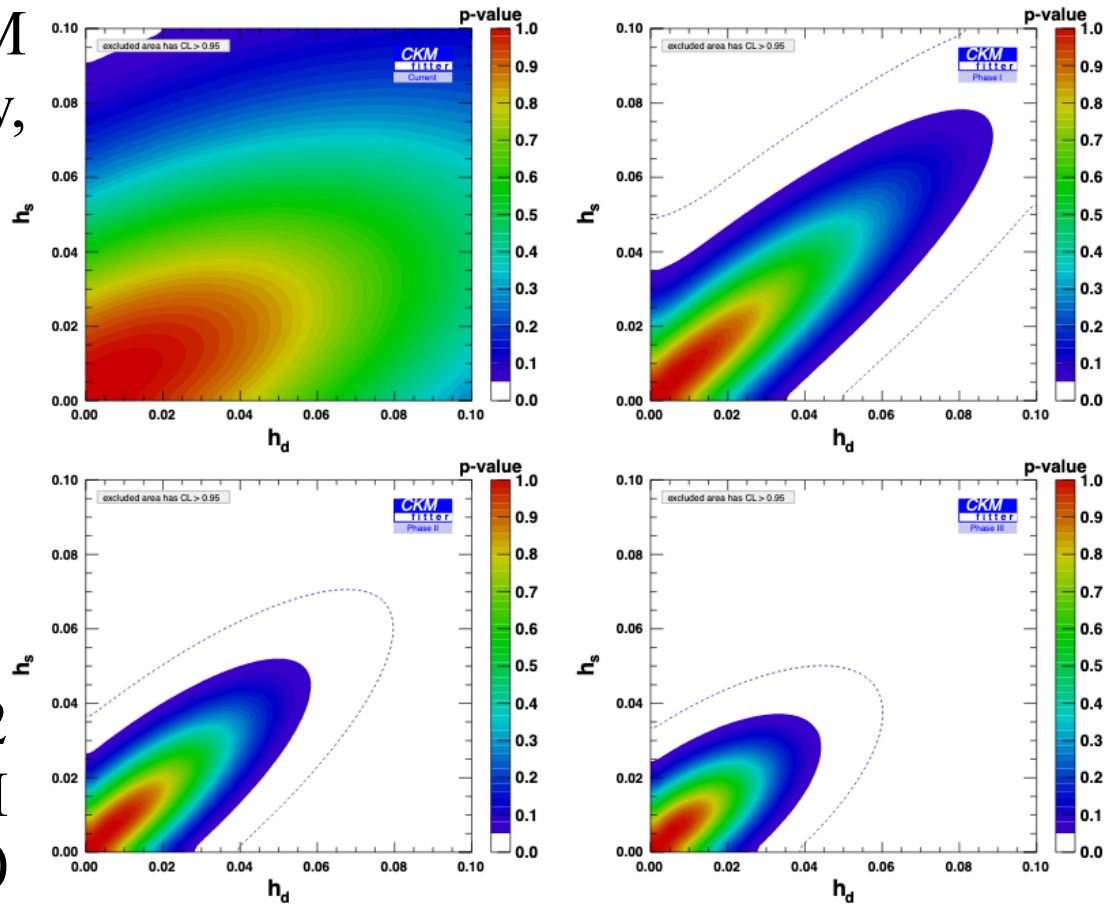
6) Focus#1: the CKM matrix element V_{cb}

FCC

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left(\frac{4.5\,\mathrm{TeV}}{\Lambda}\right)^2,$$

$$\sigma = \arg\left(C_{ij}\,\lambda_{ij}^{t*}\right),$$

hep-ph 2006.04824

rescaled to SM — Now,

after LHCb-U1 and Belle II — 2030

after LHCb U2 and Belle III — 2040

Vcb improved LQCD not

FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ) contours.

- Theory: none at W*W* threshold and beyond! Marginal correction to the *B* scale. Clean observable and hence becomes a benchmark to test the Lattice-QCD predictions.

- Experiment: this study can be a test bench for jet-flavour tagging algorithms. The latest (or close) performance of FCC-ee is tested today.
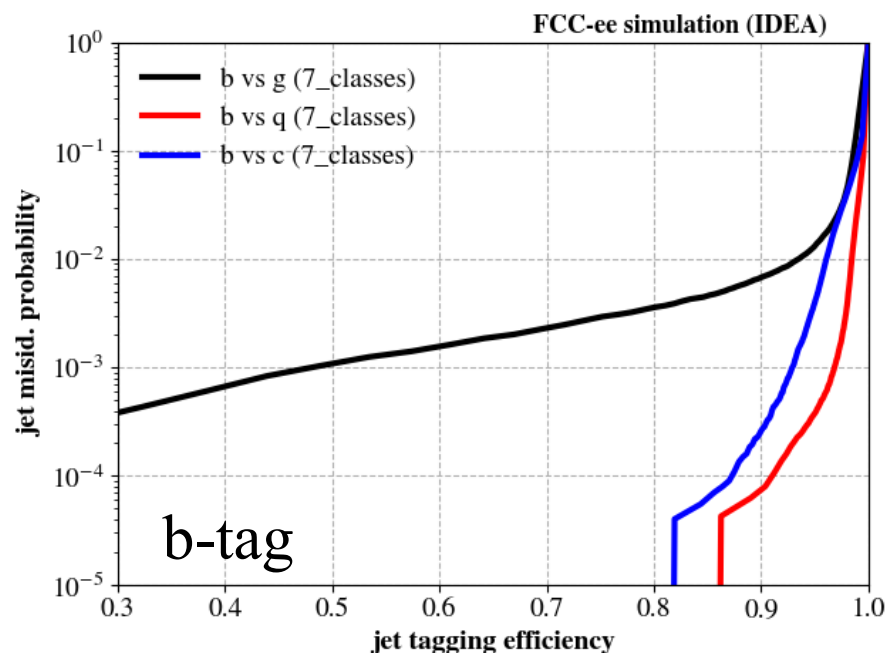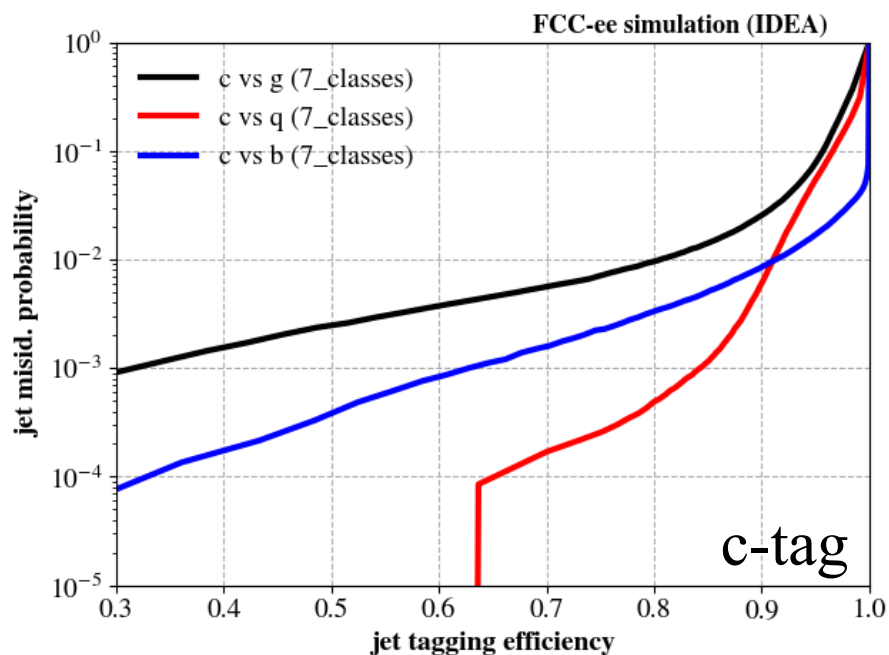
- Jet tagging performance supposed as in the previous slide
- Consider (academic) $N_{WW} = 10^8$; count the signal and background.

Eff. \	b	c	uds
b-tag	0.87		
c-tag	1	0.65	0.0001

relative precision on Vcb
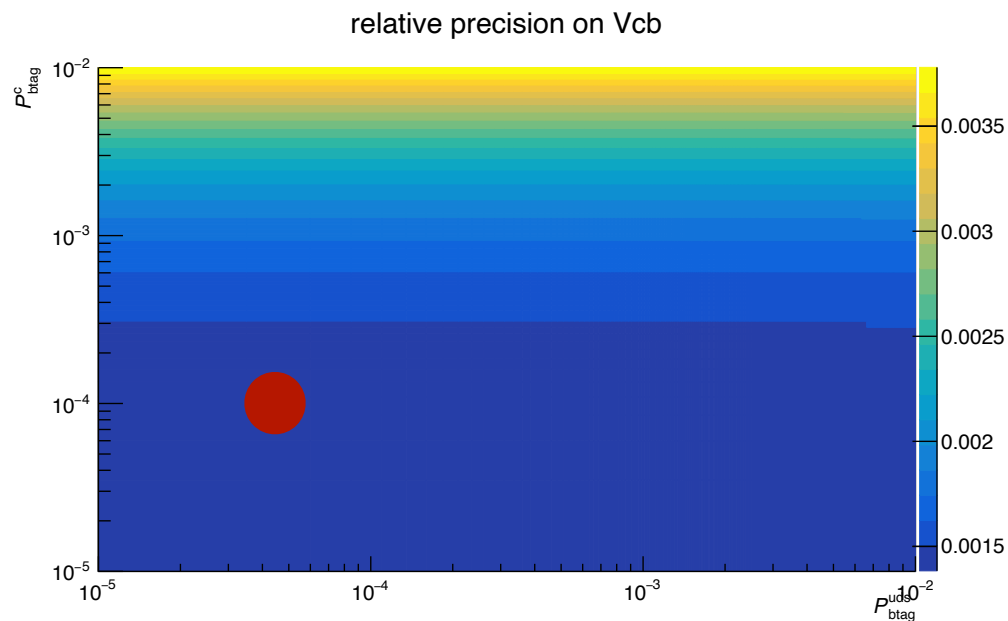
- |V_{cb}| measurement precision can be 0.15 %, one order of magnitude better than the current precision and close to the asymptotic stat. precision.
- Jet-tagging efficiencies shall be determined from data at Z-pole

The scope:

- Semileptonic decays (Electroweak penguins in the SM) with tau in the final states are not measured. First evidence with neutrinos just out!

- One of the flavour physics sectors that are beyond the reach of the current experimental programme(s). Boost at the Z / case for luminosity at the Z (FCC-ee).

- Occupied some space as a change of paradigm for the search of New Physics from the Flavour problem(s). Though the excitement has lowered with better measurements from LHCb, third fermion generation couplings are a must to study

- The canonical decays with taus places ultra-demanding requirements on the vertex detector (fully solvable kinematics provided the decay vertices are known).

FCC

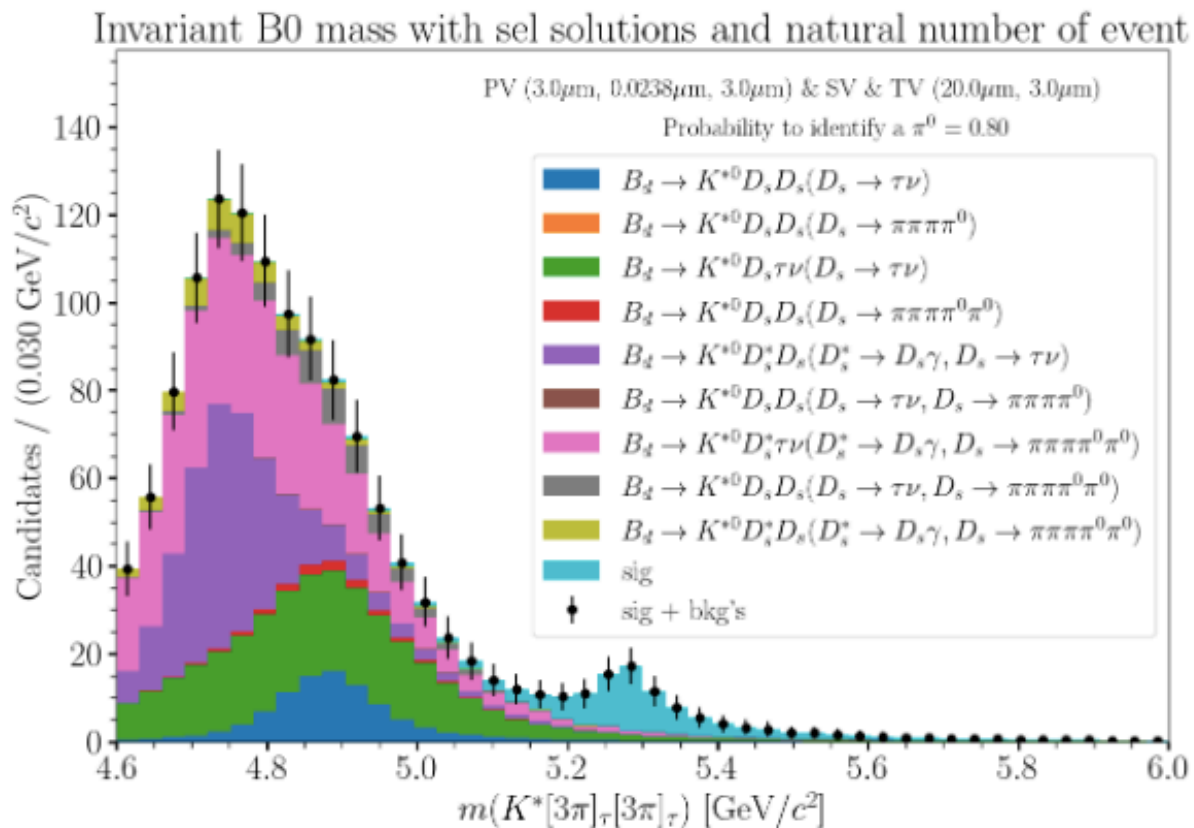- $B^0 \to K^{*0}\ \tau^+\tau^-$: some vertices indeed.
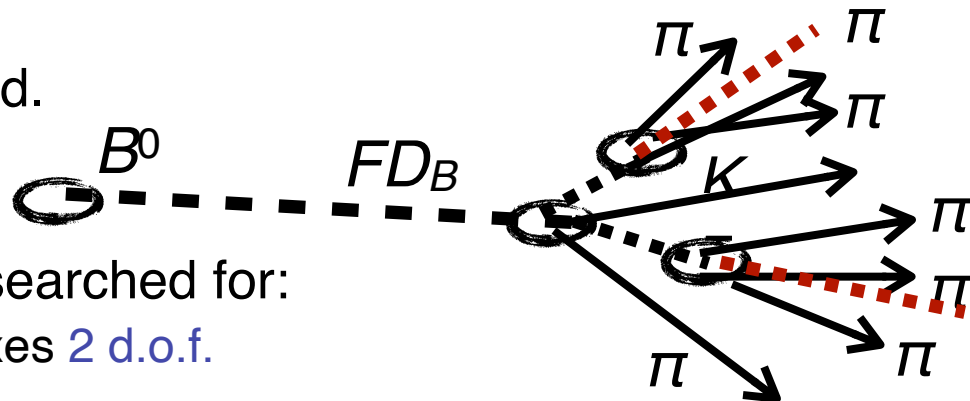
- Six momentum components to be searched for:
  - B^0 momentum direction from $K\pi$ fixes 2 d.o.f.
  - τ momenta direction fixes 4 d.o.f.
  - Mass of the τ provides 2 additional constraints
  - Since both tau legs provide quadratic equations, one ends up w/ 4 solutions.
  - Yet, the system is over-constrained and in principle fully solvable.

- $B^0 \to K^{*0}\ \tau^+\tau^-$: some backgrounds as well

Decay	BF (SM/meas.)	Intermediate decay	BF_had	Additional missing particles
Signal : $B^0 \to K^*\tau\tau$	1.30×10^{-7}	$\tau \to \pi\pi\pi\nu$, $K^* \to K\pi$	9.57×10^{-11}	
Backgrounds $b \to c\bar{c}s$:				
$B^0 \to K^{*0}D_sD_s$	2.78×10^{-4}	$D_s \to \tau\nu$	5.79×10^{-10}	2ν
		$D_s \to \tau\nu, \pi\pi\pi\pi^0$	6.52×10^{-10}	ν, π^0
		$D_s \to \pi\pi\pi\pi^0$	7.35×10^{-10}	$2\pi^0$,
		$D_s \to \tau\nu, \pi\pi\pi\pi^0\pi^0$	5.47×10^{-9}	$\nu, 2\pi^0$
		$D_s \to \pi\pi\pi 2\pi^0$	5.17×10^{-8}	$4\pi^0$,
$B^0 \to K^{*0}D_sD_s^*$	8.78×10^{-4}	$D_s \to \tau\nu$	1.83×10^{-9}	$2\nu, \gamma/\pi^0$
		$D_s \to \pi\pi\pi\pi^0\pi^0$	1.63×10^{-7}	$4\pi^0, \gamma/\pi^0$
Backgrounds $b \to c\tau\nu$:				
$B^0 \to K^{*0}D_s\tau\nu$	9.17×10^{-6}	$D_s \to \tau\nu$	3.59×10^{-10}	2ν
$B^0 \to K^{*0}D_s^*\tau\nu$	2.03×10^{-5}	$D_s \to \pi\pi\pi\pi^0\pi^0$	7.51×10^{-9}	$\nu, \gamma, 2\pi^0$

FCC

- $B^0 \to K^{*0} \ \tau^+\tau^-$: topological reconstruction + selection

Invariant B0 mass with sel solutions and natural number of event

PV (3.0μm, 0.0238μm, 3.0μm) & SV & TV (20.0μm, 3.0μm)
Probability to identify a $\pi^0 = 0.80$

Legend:
- $B_d \to K^{*0}D_s D_s(D_s \to \tau\nu)$
- $B_d \to K^{*0}D_s D_s(D_s \to \pi\pi\pi^0)$
- $B_d \to K^{*0}D_s \tau\nu(D_s \to \tau\nu)$
- $B_d \to K^{*0}D_s D_s(D_s \to \pi\pi\pi^0\pi^0)$
- $B_d \to K^{*0}D_s^* D_s(D_s^* \to D_s\gamma, D_s \to \tau\nu)$
- $B_d \to K^{*0}D_s D_s(D_s \to \tau\nu, D_s \to \pi\pi\pi^0)$
- $B_d \to K^{*0}D_s^* \tau\nu(D_s^* \to D_s\gamma, D_s \to \pi\pi\pi^0\pi^0)$
- $B_d \to K^{*0}D_s D_s(D_s \to \tau\nu, D_s \to \pi\pi\pi^0\pi^0)$
- $B_d \to K^{*0}D_s^* D_s(D_s^* \to D_s\gamma, D_s \to \pi\pi\pi^0\pi^0)$
- sig
- sig + bkg's

y-axis: Candidates / (0.030 GeV/c^2)
x-axis: $m(K^*[3\pi]_\tau[3\pi]_\tau)$ [GeV/c^2]

- $B^0 \to K^{*0} \ \tau^+\tau^-$: we could see unambiguously the SM signal with this emulated detector! But it is an arbitrarily good one.

- $B^0 \to K^{*0}\ \tau^+\tau^-$: Checking how much to improve a vertex detector design? The IDEA example @ FCC-ee.

Precision of BF measurement as function of the resolution
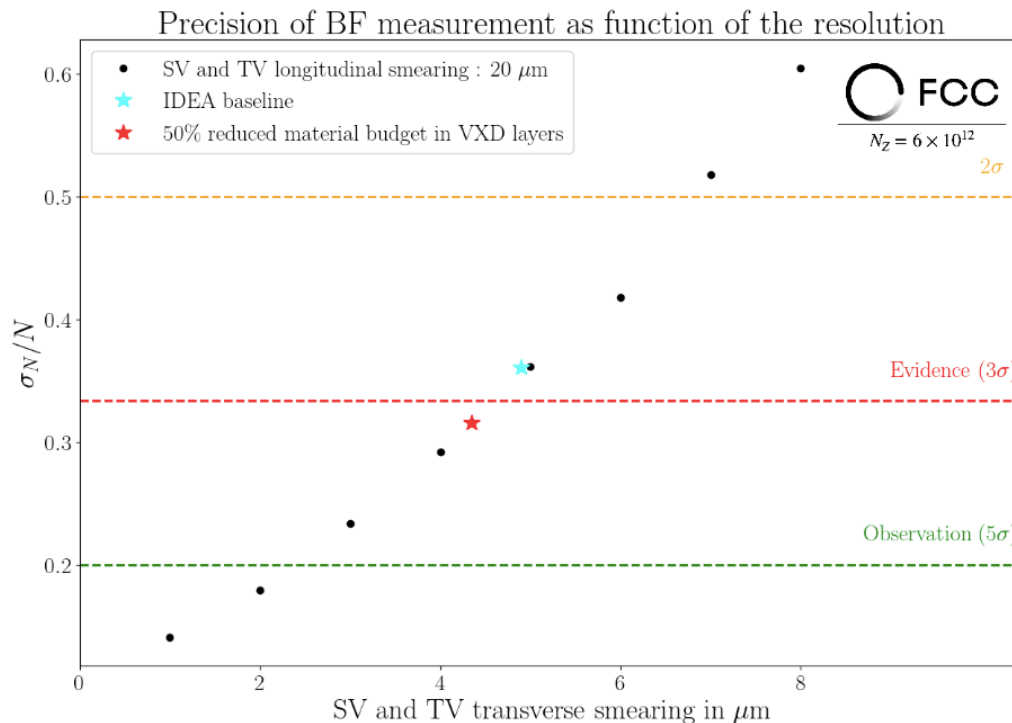
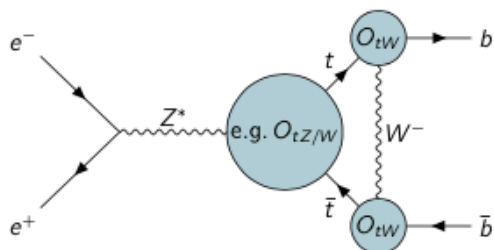- One lesson: need to reduce the material of the beam pipe, or better, put the vertex detector in the beam pipe.
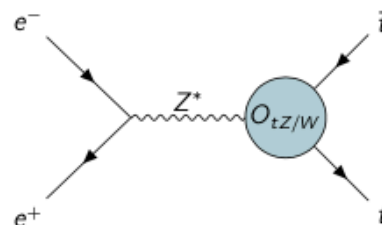
FCC
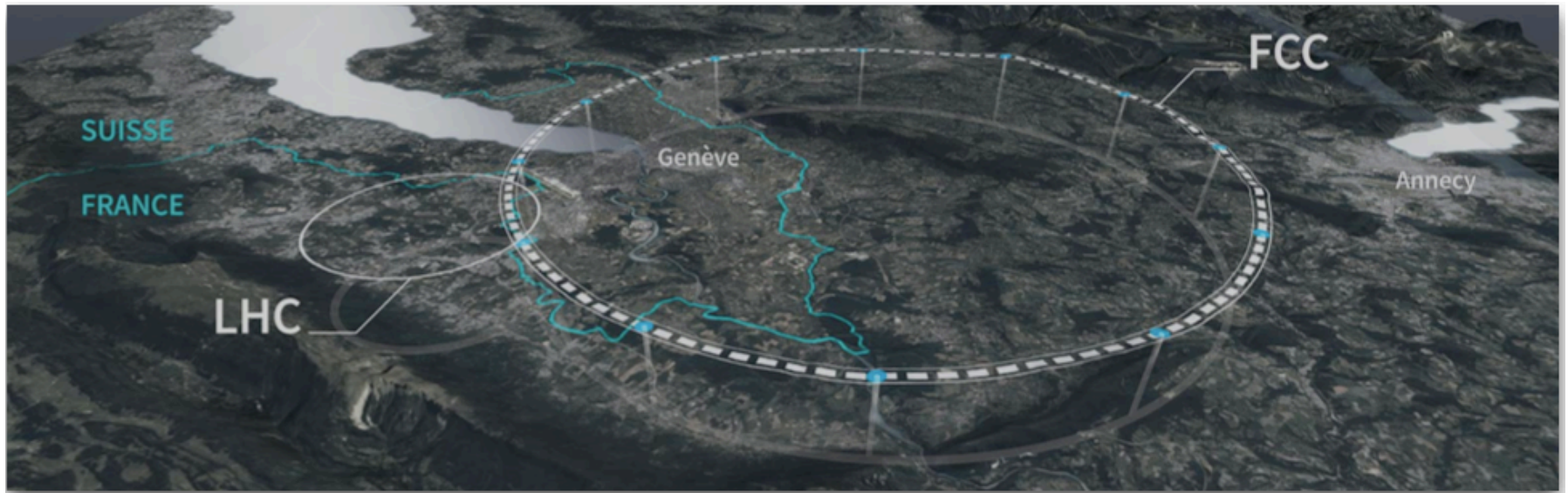
Motivation I

- Possible anomalies translate over a range of energy scales: from Z-pole to top threshold
- Heavy-quark EW measurements as a **probe for new physics** with a common set of dimension-6 operators

$\mathcal{O}(m_Z) \sim 90$ GeV

$\mathcal{O}(m_t) \sim 350$ GeV to 365 GeV

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Today:
- Measurements at the Z-pole with $4.2 \times 10^{12}\ Z \to q\bar{q}$ (4 IPs):
  - $R_b = \frac{\sigma_{b\bar{b}}}{\sigma_{\text{had.}}}$
  - $A_{\text{FB}}^b = \frac{N_F - N_B}{N_F + N_B}$
  → Likely **dominated by systematic uncertainties**
  → Explore Tera-Z regime with **exclusive b-hadron decay reconstruction as new tagger**

Novel methods in order

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Exclusive *b*-hadron decays

- LEP $\sigma_{\text{syst.}}$ dominated by *udsc*-physics and hemisphere correlations
- With Tera-*Z* $\sigma_{\text{stat.}}$ in reach: measurement limited by systematic uncertainties
- Reconstruct exclusive *b*-hadron: determine quark-flavour with 100 % purity
  → Stick to **ultra-pure mass region** to assess remaining systematic uncertainties → $\varepsilon_b = 1\%$

| Observable	R_b	A^b_{FB}
b-hadrons	$B^+, B^0_d, B^0_s, \Lambda^0_b$	B^+, Λ_b
Knowledge of...	Flavour	Flavour, $\vec{p}$ & Q
Advantages	Remove *udsc*-physics contribution	Overcome mixing dilutions and hemisphere confusion
Remaining $\sigma_{\text{syst.}}$	Hemisphere correlation C_b	QCD corrections
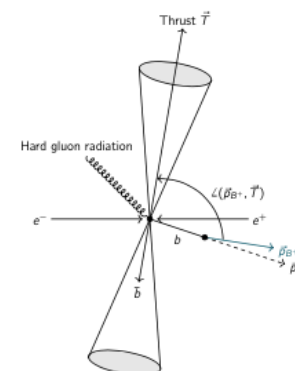
- C_b and QCD corrections evaluated on **Full Simulation sample** and forced decays ($B^\pm \to [K^+\pi^-]_{\bar{D}^0} \pi^+$)

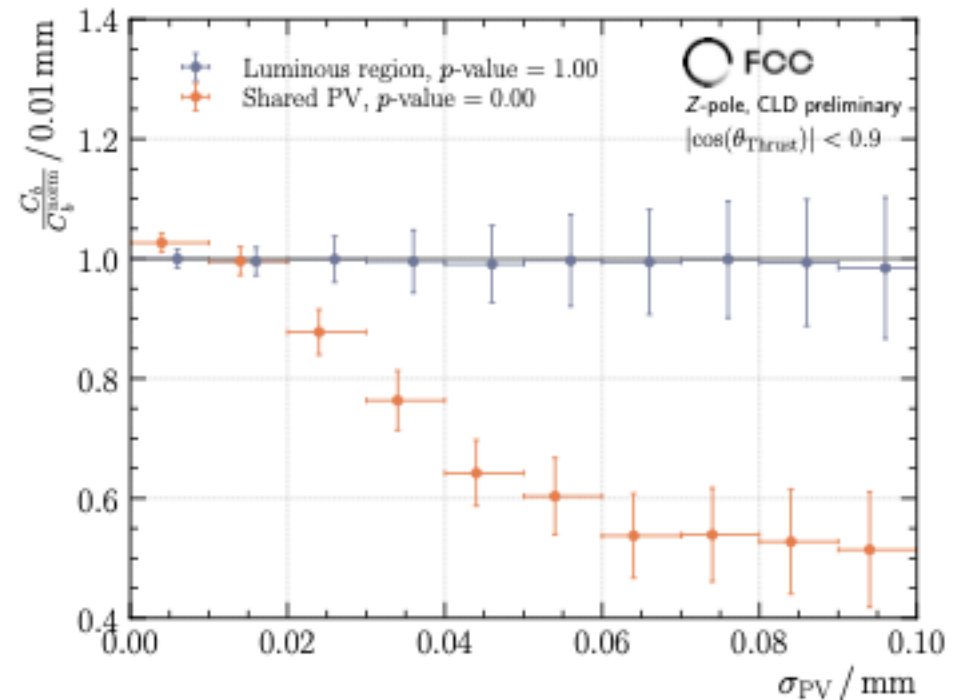- Here: $B^+ \to [K^+\pi^-]_{D^0} \pi^+$ with $E_B > 20$ GeV to reduce background

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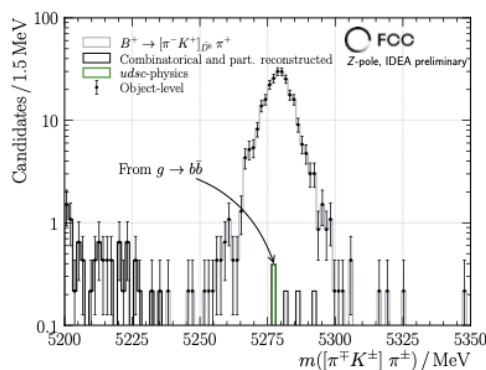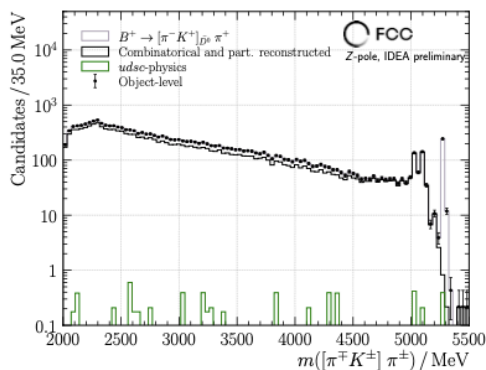
- Understanding hemisphere correlations as the ultimate systematics

- LEP found that PV resolution was driving the correlation. LEP did separate PV measurement per hemisphere.

- At FCC-ee, one can use the luminous region to reduce the correlation.


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S. Monteil

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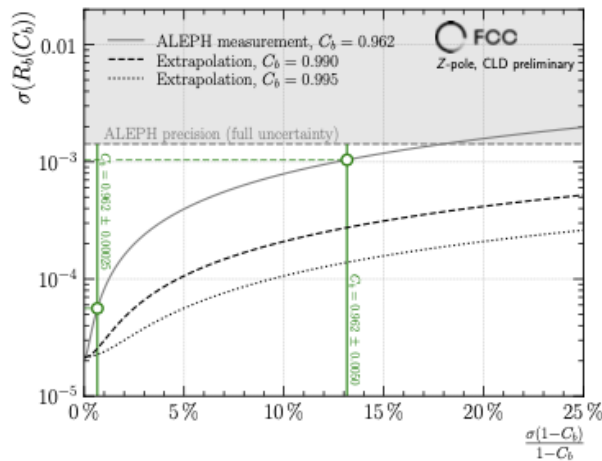
- Exclusive decays as a tagger can also help to reduce the systematic uncertainties on the bb forward-backward asymmetry

- Light quark contamination and mixing dilution are removed by the performance of the tagger.

- Remaining uncertainty to tackle are therefore QCD corrections. Could be controlled by the angle b/w thrust and the b-hadron candidate.

- Seems as well promising.

- Work in progress!

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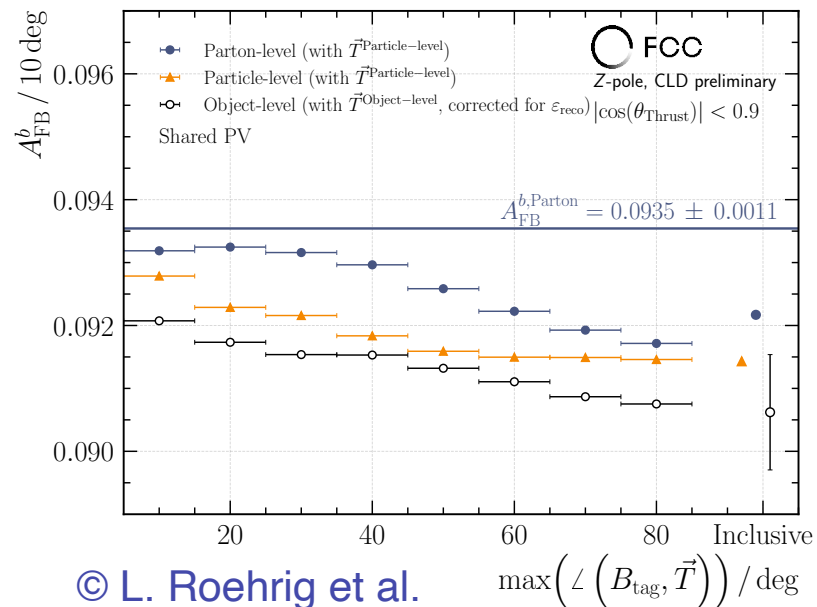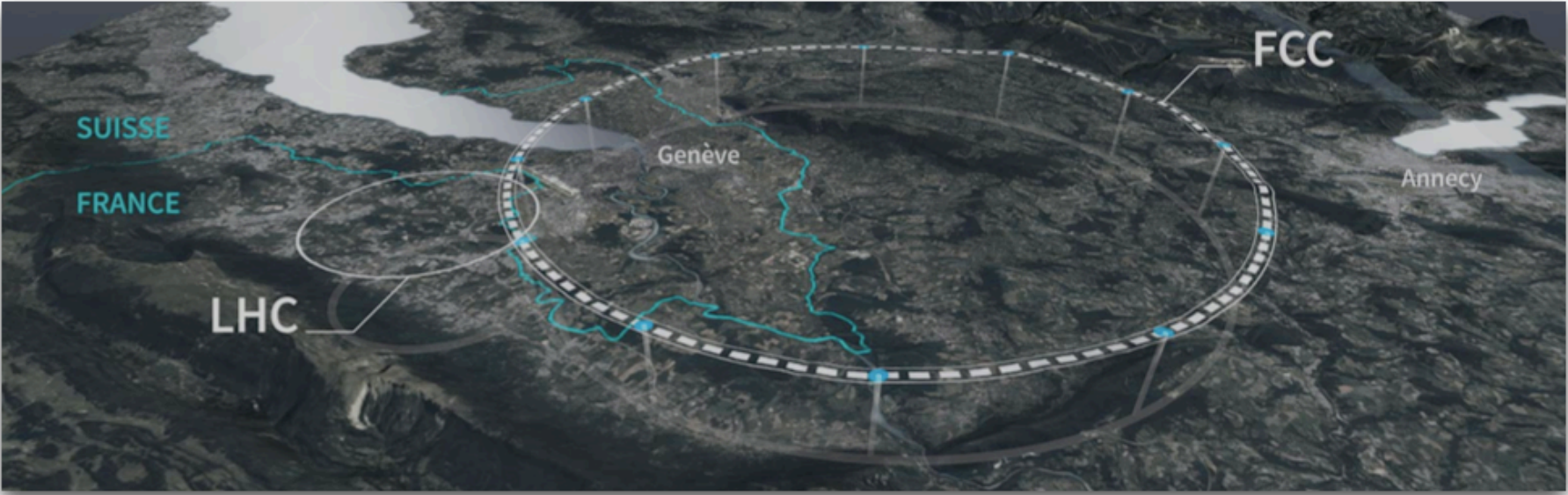
8) Conclusions

- FCC-ee is the proposal at CERN for the next e^+e^- Higgs factory.

- It is much more than a Higgs factory:

  - Z factory [$O(10^{13})$]
  - b, τ, c factories [$O(10^{12})$]
  - W factory [$O(5.10^8)$]
  - top factory [$O(10^6)$]

- The mid-term review went well (I was told). Conclusions to be analysed / endorsed by the CERN council (02/02/2024).

- There's a vibrant program for Flavour Physics for the next two decades: the completion of Belle II and the desirable advent of the second LHCb upgrade (300 /fb). Our knowledge will improve a lot.

- FCC-ee is allowing for a continuation of the Flavour program and to deepen it further. Four IPs —> one flavour-oriented detector.

FCC

- Flavour Physics provides several areas to engage in the Feasibility Study, with consequences on the desirable detector concepts. Major requirements for calorimetry and vertexing. A flavour-oriented detector concept is still to be proposed.

- Generation of your favorite decay with EvtGen is available.

- Common analysis tools are steadily being put in place (secondary vertex finding available!).

- Several platforms as well where to contribute. To get in touch:

  - FCC-ee Flavour group: G. Isidori, J. Kamenik, A. Lusiani, SM.
    - FCC-PED-PhysicsGroup-Flavours-admin@cern.ch
  - ECFA Flavour group: P. Goldenzweig, D. Marzocca, SM.
    - ECFA-WHF-WG1-FLAV-conveners@cern.ch

- Example: degree alpha measurement : a study to get started.

- The alpha angle can be measured through an isospin analysis from $B^0 \to (\pi\pi)^{+-/00}$. The knowledge of parameter S^{00}, that can be accessed from time-dependent studies, allows to lift degeneracies among solutions.
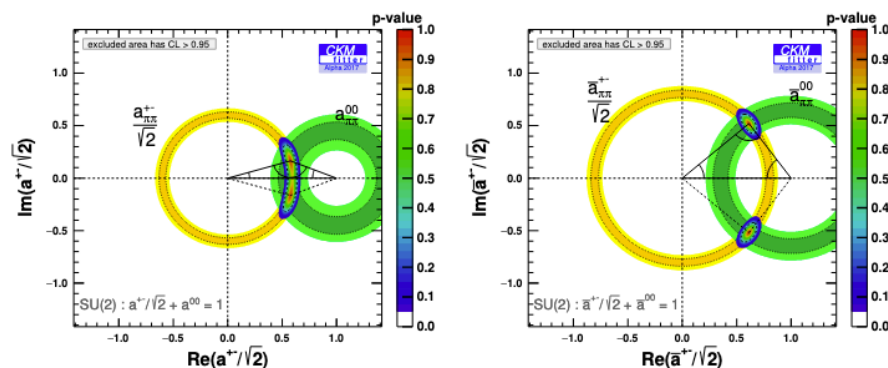

Figure 4: *Constraint on the reduced amplitude $a^{+-} = A^{+-}/A^{+0}$ in the complex plane for the $B \to \pi\pi$ (left) and $\bar{B} \to \pi\pi$ systems (right). The individual constraint from the $B^0(\bar{B}^0) \to \pi^+\pi^-$ observables and from the $B^0(\bar{B}^0) \to \pi^0\pi^0$ observables are indicated by the yellow and green circular areas, respectively. The corresponding isospin triangular relations $a^{00} + a^{+-}/\sqrt{2} = 1$ (and CP conjugate) are represented by the black triangles.*

- Accessible through Dalitz decays of the π^0 in $B^0 \to (\pi^0\pi^0)$. Vertex is there. Statistics too [O(10k)]. A possible case study for EM calo. design.

- Flavour Physics defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements. The feasibility study entangles the Physics performance and detector concepts. Flavour physics places most demanding requirements for vertexing and calorimetry.

- The feasibility study will be used to systematically address the physics case while placing requirements on the detectors. Hadron particle identification deserves a special treatment and Flavour physics is at the heart of it.

- All studies at the Z pole shown above are made for 5.10^{12} Z decays. Most of flavour observables will remain statistically limited. More would be desirable ! The machine study from two IPs to four IPs is positive and would bring about a factor 2 (1.7) in integrated luminosity.

- Four experiments can as well allow for different experiment designs, including a flavour-oriented concept.

- Engage and reach out to make this plan happening.

- Two illustrations:

  - 2) From radiative decays: separation of $b \to s\gamma$ and $b \to d\gamma$. *Academic exercise w/ $B^0 \to K^*\gamma$.*
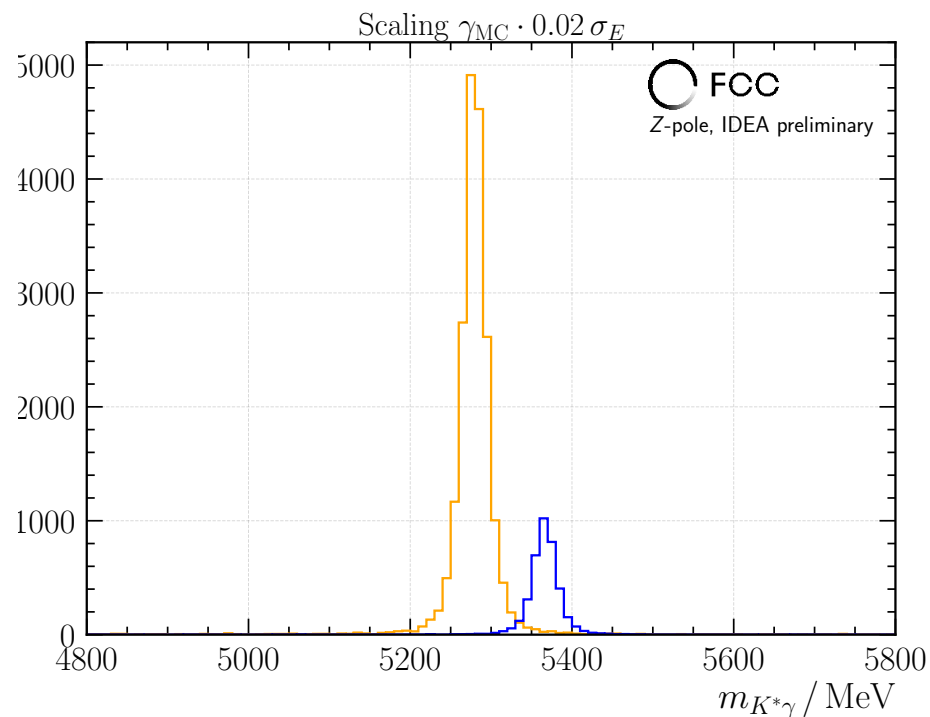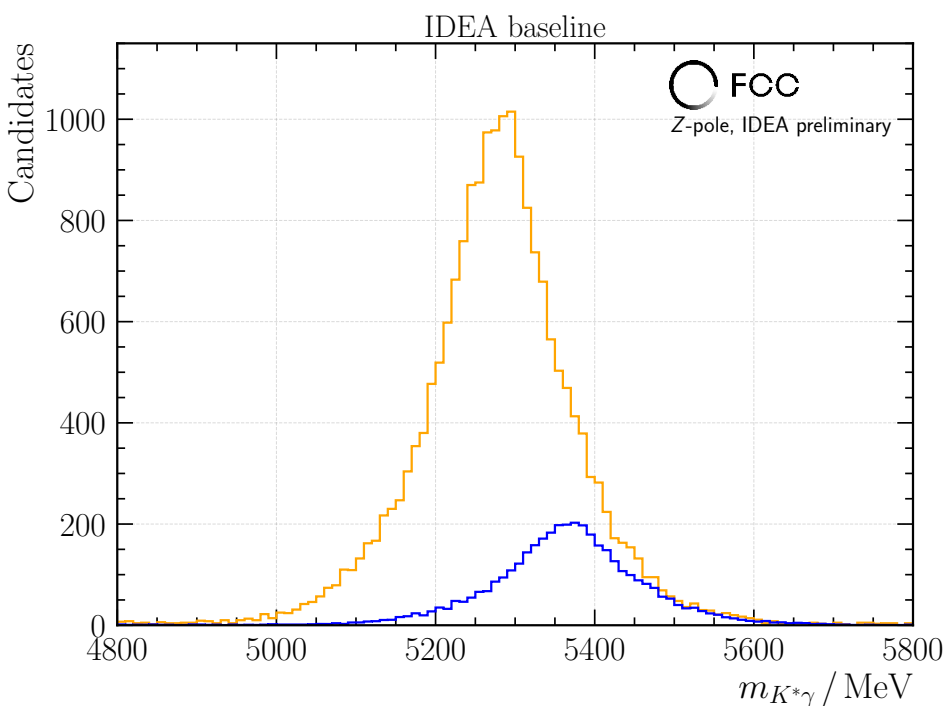
- There's a difference! addressing or not this Physics.